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Contributions of local farming to urban sustainability in the Northeast United States

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Abstract

Food consumption is an important contributor to a city's environmental impacts (carbon emissions, land occupation, water use, etc.) Urban farming (UF) has been advocated as a means to increase urban sustainability by reducing food-related transport and tapping into local resources. Taking Boston as an illustrative Northeast US city, we developed a novel method to estimate sub-urban, food-borne carbon and land footprints using multi-region-input-output modeling and nutritional surveys. Computer simulations utilizing primary data explored UF's ability to reduce these footprints using select farming technologies, building on previous city-scale UF assessments which have hitherto been dependent on proxy data for UF. We found that UF generated meagre food-related carbon footprint reductions (1.1-2.9% of baseline 2211 kg CO_2 equivalents/capita/annum) and land occupation increases (<1% of baseline 9000 m^2 land occupation/capita/annum) under optimal production scenarios, informing evidence-based urban design in the region. Notwithstanding UF's marginal environmental gains, UF could help Boston meet national nutritional guidelines for vegetable intake, generate an estimated $160 million US in revenue to growers and act as a pedagogical and community building tool, though these benefits would hinge on large-scale UF proliferation, likely undergirded by environmental remediation of marginal lands in the city.

Introduction

Food consumption is a key driver of a city's environmental burdens[1,2], and in the United States (US) per capita impacts are amongst the highest globally[3,4]. Many cities in the Northeast US are promoting urban farming (UF) – food production within the city, allowing for material and energy exchange between city and farm[5] – as a joint environmental and social sustainability exercise[6,7]. Up to 20% of global food supply already comes from within cities, primarily in the Global South[8,9], but the potential in the Global North's cities to produce their own food on the ground and buildings is believed to be substantial[10–12]. Hypothetical assessments of UF at the city-scale have demonstrated reduced food related GHG emissions[13,14] and land occupation[14], giving the impression that pro-UF policies can contribute to more sustainable urban food supply networks. Despite UF's perceived environmental benefits, the recent spurt of pro-UF actions by the cities of the Northeast US that include codification in land use laws[7,15] and multi-city commitments to increased local food production[6] require deeper reflection about their systemic environmental implications.

UF advocates tend to focus on the distance from farm to fork, equating local food with environmentally sustainable food[16,17], oversimplifying the complexity of food sustainability to a single aspect. Reducing distribution burdens and wastage by co-locating food production and consumption can lead to environmentally leaner production networks[18,19], but contrasting results have been found when large energy inputs are needed for space heating and lighting[20,21]. UF in the Northeast US has demonstrated lower embodied greenhouse gas (GHG) emissions compared to conventional supply networks in some instances, but with tradeoffs in other indicators (land occupation, water scarcity) and potentially significant burdens from farm capital[21]. UF studies at neighborhood and city scales have estimated reductions in food-borne GHG emissions[13,14] and land occupation[14], although these findings are not transferable to the US Northeast due to climatic differences. The use of data for conventional agricultural production (minus transport and wastage) as a proxy for UF production due to data gaps[13,14] biased the assessments in UF's favor.

This article provides a level of analysis that has been absent in previous UF sustainability work. We used primary data from multiple urban farms in the US Northeast to evaluate the environmental tradeoffs of substituting UF for conventional produce at the city-scale in this region (assessing strictly horticultural products), including interactions with the host city's material and energy systems. Multi-region input-output based environmental life cycle assessment (MRIO-LCA) was combined with nutritional surveys to model baseline food-borne environmental burdens at sub-urban granularity, in contrast to earlier work that has assumed equivalency between per capita city and national food intakes. Potential nutritional and economic benefits of UF were also considered.

Boston, US was used as a representative case city for the Northeast US. Though denser than many cities in the region, Boston's monocentric layout typifies most Northeast US cities, particularly in the densely populated Northeast Megalopolis. Importantly, Boston's climate mirrors that of the Northeast US, with an outdoor growing season roughly from April through October, and cold winters necessitating indoor growing reliant on external heating from the region's predominantly fossil-fuel driven grid.

Methods

Two overarching tasks were performed here: estimating baseline environmental impacts from Boston's food demands and modeling UF in Boston.

Baseline environmental performance

EXIOBASE v2.3 MRIO model was applied to estimate Boston's food related environmental burdens in 2010. EXIOBASE is a trade-linked model accounting for global economic activity in 2007, detailing domestic production, bilateral trade and final consumption of 43 regions accounting for ~90% of global GDP[22]. MRIO-LCA has been described in detail elsewhere[23,24], but the method's core are environmental extensions coupling production activities to resource and pollution intensities per unit economic output, facilitating the allocation of environmental impacts and resource draws to end consumers. Such top-down analysis is suitable for consumption based environmental accounting of large systems, having been applied at the national[25–27] and urban scales[28,29]. We chose EXIOBASE due to the high level of disaggregation (200 products), including pertinent food items.

The assessed indicators were land use and global warming potential (GWP). Land use accounts for crop, pasture and forest land occupation in m^2. The GWP extension includes CO_2, CH_4, N_2O and SF_6 emissions, employing IPCC 2013 methodology to convert emissions to the radiative forcing in equivalent mass CO_2 over a 100 year time horizon (kg CO_2e).

Input-output models take the product of national footprint multipliers (e.g. kg CO_2e/$ final demand product) and final consumption ($ final demand for product) to estimate demand-side footprints, insinuating that doubling food expenditures doubles food consumption and environmental stress. Whilst there is a correlation between income and food related environmental burdens at the national scale, it appears to follow a logarithmic trend, hinting at an income level beyond which food intake and environmental impacts plateau[1,3]. For a wealthy nation such as the US with a low Engel's ratio[30] (food expenditures as a percentage of total income), assuming a linear relationship between food expenditures and consumption is erroneous. US nutritional surveys show slight differences between the food consumption of high and low income residents, most notably for environmentally intensive foods (less than 10% difference between the groups for per capita meat and dairy intake by mass)[31], despite markedly elevated food expenditures by wealthy Americans[32]. Lastly, the higher prevalence of obesity in poorer Americans highlights the incongruences between food expenditures and intake[33].

We circumnavigated this challenge using a top down approach, ascribing total GWP and land use from US final food consumption to total available calories in the US, akin to Jones and colleagues[28,29]. Using a concordance matrix linking calorific availability for over 200 foods with products in the EXIOBASE model (e.g. calories of grains with the EXIOBASE product 'Cereals'), embodied environmental intensity per calorie was estimated. Total calories available for different foods were taken as the product of the 2007 US population and average US calorific intake for the years 2007-2010 from the Center for Disease Control's National Health and Nutrition Examination Survey (NHANES)[34] corrected for supply chain losses using US Department of Agriculture (USDA) loss adjusted availability data[35]. Tables S1 to S24 in the supplementary information document this process.

Intakes of foods for US demographics based on sex and age group were taken from the NHANES data for 2007-2010. Sex and age were chosen to develop population sub-groups as these are both strong determinants of food volume consumed (males tend to eat more than females at most ages) and dietary habits (e.g. dark green vegetable intake is nearly zero before age 14 and then proceeds parabolically with age)[34]. This sub-grouping also allowed for more nuanced modelling than the low/high income binary afforded by the publically available NHANES data relating income to food intake[31]. Demographics data for Boston at the block-group level (geographies of population 600-3000) were taken from the 2010 US Census. Combining census data, calorific intakes for different demographics and embodied GWP and land use per calorie delivered, food-borne environmental burdens for 560 block-groups in Boston were calculated. Figure 1 outlines this workflow while the supporting information details the data manipulation and calculations.

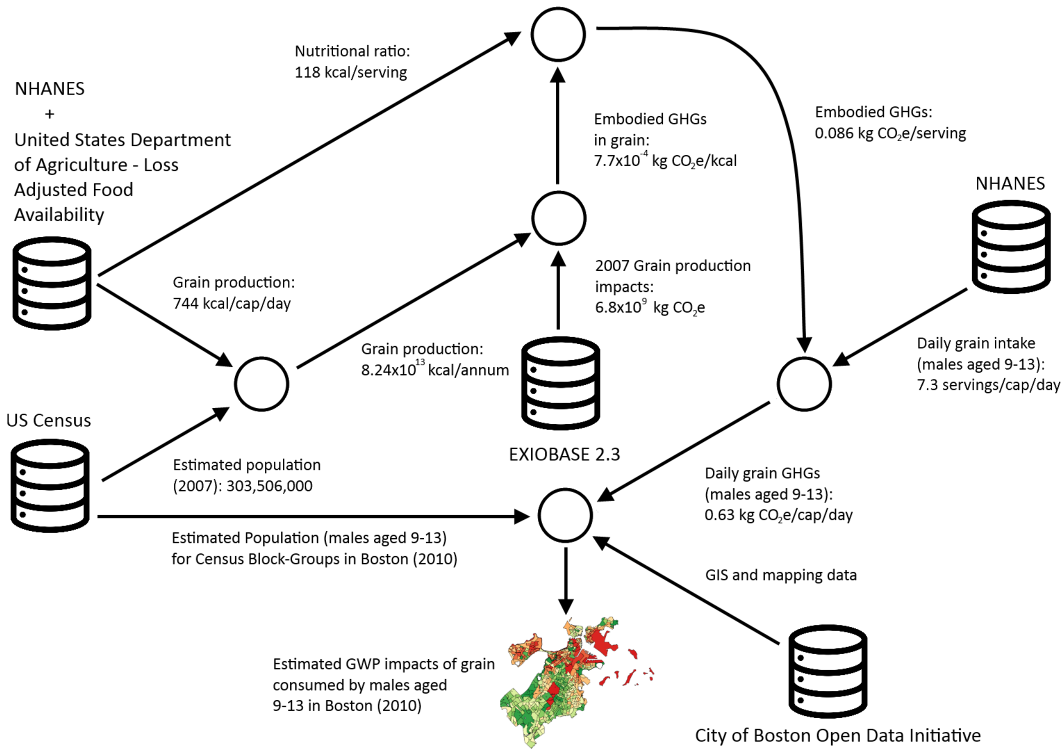

Figure 1. Workflow in generating baseline environmental performance, using grain consumption by adolescent males as an example.

Modelling UF in Boston

We assessed two UF forms: empty-lot and rooftop farms, both open to the ambient environment. Data were also collected on additional UF forms (ground/rooftop greenhouses and automated precision agriculture), but were not included in the model since they displayed worse environmental performance compared to conventional produce[21], and therefore, were poor candidates when assessing UF's substitution benefits. Resource use and yield data for two empty-lot farms and one rooftop farm were collected over the 2015 growing season for 14 vegetables covering 32% by mass (44% excluding potatoes) and 24% by calories (50%

excluding potatoes) of total average US vegetable consumption[35]. Although only some of the 14 vegetables were environmentally preferable to conventional when produced with UF (see supporting information), including all vegetables was representative of actual production scenarios where farmers are free to choose their crops.

GWP and land use impacts from UF production were modeled with process-LCA from cradle to point of purchase, aligning with the EXIOBASE scope (transport impacts were added manually to EXIOBASE results) and capturing the majority of food related impacts[36–38]. Conventional crop GHG intensities were taken as mean values from Keolian and Heller's review of food LCAs[39], corrected for distribution losses and average transport distances. Land use was taken as direct agricultural land occupation from USDA production data[40], corrected for distribution losses[35], and excluded final distribution burdens. LCA modelling details are in the supporting information.

Ground space potentially available for UF was determined using *additive* and *subtractive* approaches. The additive approach assessed over 160,000 individual properties in Boston, calculating total UF space as the sum of properties with land uses amenable to UF (vacant lots, pasture, open land, cropland, transitional, etc.) The subtractive approach started with the city's entire land area and subtracted land uses unsuitable for UF (steep slopes, impermeable surfaces, protected parkland, etc.) to arrive at an upper estimate from the opposite direction. Rooftop UF space was estimated using a dataset of 80,000 buildings in Boston. Lacking structural data, the year of construction was used as a proxy for load bearing ability. We tested cutoff years from 1900 to 2000 to quantify the effect of this choice on model results since this range covered ~80% of the city's buildings. Buildings over 30 meters high, having sloped roofs or historically protected were assumed unusable for UF. As some buildings lacked data on roof-type, 100-run

Monte-Carlo simulations were performed for each cutoff year, examining the impact of probabilistic roof-type assignment. The supporting information details the UF area estimates.

In considering UF interactions with the city we included avoided runoff, municipal organic solid waste assimilation and building energy impacts. High and low estimates of runoff reduction were taken as the average rainfall in Boston times the formally impermeable UF area, using upper and lower retention values from previous studies[41,42]. Solid waste assimilative capacity was taken from primary data on urban farm compost consumption converted to mass of original organic waste. The same dataset used in calculating roof space includes heating and air conditioning data which were combined with commercial[43] and residential[44] energy surveys to estimate building energy loads. Previous studies of heating and cooling savings from vegetated roofs were used to estimate energy savings from building situated UF[45]. UF interactions with Boston's hydrological, waste and energy systems are detailed in the supporting information.

We modeled the most efficient application of Boston's UF space towards both land use and GWP reduction. An algorithm was run whereby each block-group produced vegetables that resulted in the largest reduction in GWP or land use depending on optimization goal, while respecting local demands for each crop as a constraint. Space was allocated to a vegetable until the block-group was satiated (at which point the next best vegetable for the optimization goal was produced), UF space was exhausted or all vegetable needs were met. After all blocks-groups had the chance to produce for themselves, those with extra capacity produced for those lacking space until total vegetable needs for the city were met or Boston's UF space was exhausted. See supplementary information for detailed explanation of optimization algorithm.

Given the different UF space estimation methods and optimization goals, four scenarios were run. Within each scenario 10 different building age cutoffs were considered using 100-run Monte-Carlo simulations. Table 1 outlines these scenarios.

Scenario	Description
GWP(+)	Optimization for GWP reduction using additive method to estimate UF space
GWP(-)	Optimization for GWP reduction using subtractive method to estimate UF space
Land(+)	Optimization for land use reduction using additive method to estimate UF space
Land(-)	Optimization for land use reduction using subtractive method to estimate UF space

Results and Discussion

Figure 2a shows the average, baseline GWP for Boston's food demands according to the NHANES usual daily intakes for different demographics. Calculated GWP was 2211±55 kg CO_2e/cap/a aligning with national assessments using EXIOBASE[27], with the main impacts emanating from the meat and dairy products (54%). Figure 2c focuses on GWP impacts for the individual block-groups which varied between 2078-2211 kg CO_2e/cap, where those with greater proportions of adults and males sat at the upper end. The influence of meat and dairy agrees with other assessments of the US diet[29,38,39]. GWP estimates are larger than process-LCA accounts of the US diet[39], but well aligned with other input-output analyses of US food consumption[28,38], a result of the latter method's enhanced value-chain coverage when building inventories. The tight spread around Boston's mean and proximity of city and national averages support the use of the latter as a proxy for urban level impacts, though caution is warranted when using this simplification in settings with substantial income inequality.

Figure 2b presents land related impacts which averaged 9077±198 m^2/cap/a (8578 to 10554 m^2/cap/a), agreeing with the earlier national EXIOBASE work[27] and studies that have pegged average US food-related land occupation between 0.86-1 ha/a[46,47]. Meat and dairy were again dominant (~50%), while fruits and vegetables were also key (20%). The focus on animal based products agrees with previous work, but the percentage of total land burdens is reduced. Peters et al.'s assessments of US diets have found that animal products accounted for approximately 75% of the ~1 ha/a land use burdens[46,47], and Eshel and colleague's calculate over 1 ha/cap/a for animal-sourced foods alone[48]. Misalignment with these other studies might stem from the calorie allocation method employed here, since EXIOBASE products divided between animal- and vegetal-sourced foods (e.g. 'Food products nec' a catch-all EXIOBASE product for various processed foods, accounting for 39% of total land use) are disproportionately allotted to the latter, due to the poorer energetic returns per unit area when moving up trophic levels[47,48].

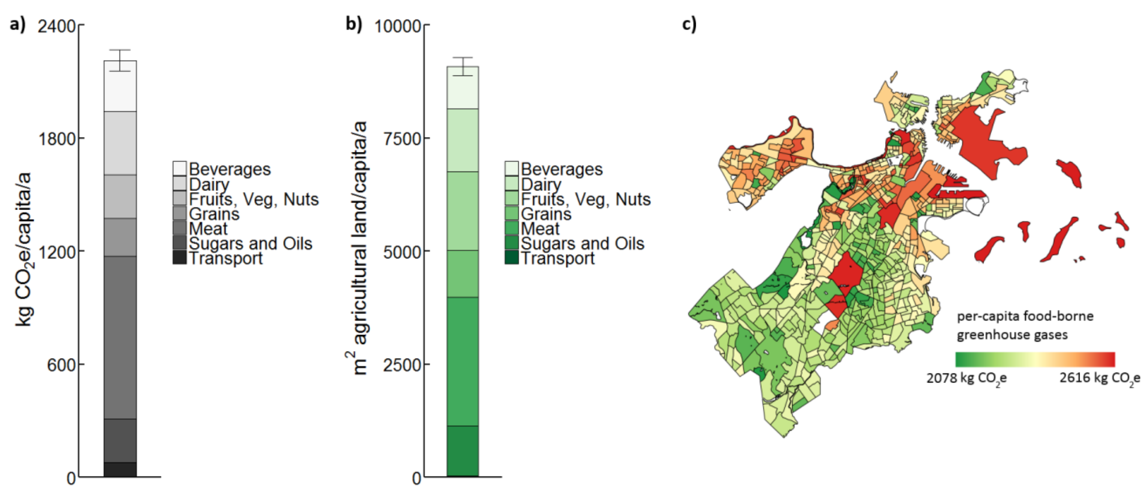

Figure 2a-c. Average baseline food related (A) GWP and (B) land use impacts for Boston in 2010 based on NHANES demographic usual daily intakes. Error bars represent standard error amongst city population. (C) Average GWP at the block-group level, with uninhabited blocks shown as white.

Available UF space

Figures 3a-b show Boston's available ground UF space calculated with subtractive and additive methods estimated at 8846 and 2000 acres (28.8% and 6.7% Boston's area), respectively. Naturally, the lower density block-groups with dispersed built forms tended to have more UF potential, but appreciable area was also found in the former industrial areas and port lands. These estimates ignored contaminated land that would likely be precluded from UF without remediation, but are suitable approximations of where UF could be placed without disturbing Boston's built form. Figure 3c-d presents 100-run Monte Carlo average UF available roof area in each block-group for the lowest (1900) and highest (2000) construction cutoff years, respectively. A 1900 cutoff resulted in 8828 available UF buildings with average area 195 m^2 netting 424±8 total acres. Using 2000 as a cutoff year left only 700 buildings with a mean area of 379 m^2, covering a mere 26±3 acres. The majority of Boston's buildings were built prior to 1920, and accordingly, estimated rooftop UF space remained below 200 acres at cutoffs above this year (see supplementary information figures for further details).

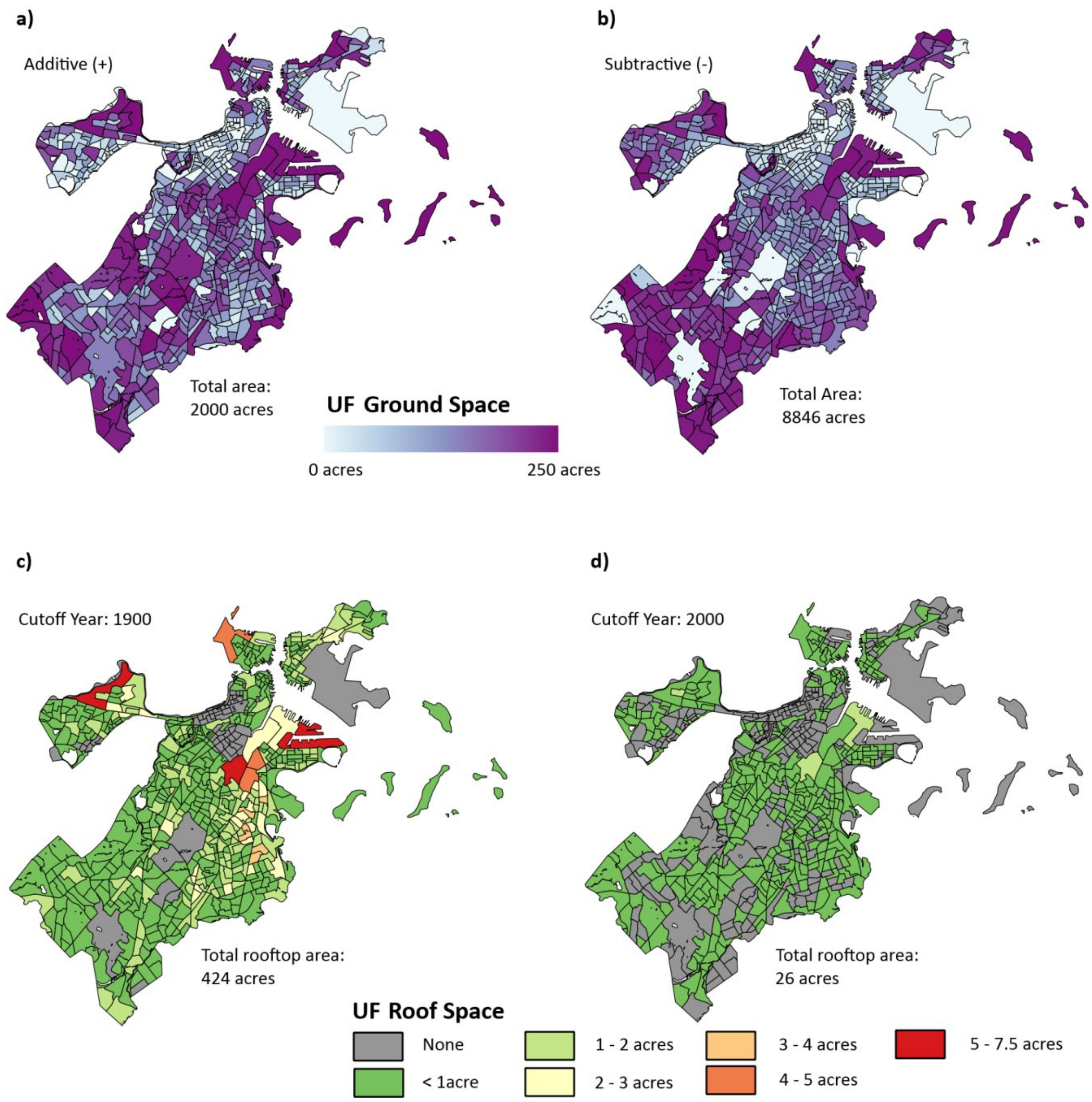

Figure 3a-d. Ground UF space in individual block-groups in Boston using (a) additive, (b) subtractive and rooftop space using construction year cutoffs of (c) 1900 and (d) 2000.

Environmental performance of UF

Figure 4a exhibits the changes in GWP potential through the introduction of UF into Boston for the four scenarios. Results average all Monte-Carlo runs and all years for each scenario. The GWP(+) scenario provided 20% greater GHG reductions compared to the Land(+) (18066±432 vs. 15045±523 tons CO_2e/a). With the subtractive method both GWP and land optimizations approached each other (~24000 tons CO_2e/a) since they both produced until Boston’s demands for the UF crops are met, with slight differences due to allocation choices (ground vs. roof) for select vegetables. In the best cases, UF reduced Boston’s total food-borne GWP burdens by approximately 1.1% (12% of fruit and vegetable burdens) when limited by space, and by 1.3% (15% of fruit and vegetable burdens) when producing until vegetable demands were met.

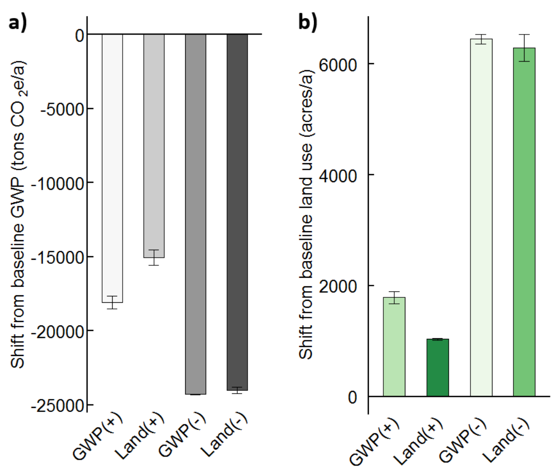

Figure 4. Impacts of UF on (a) GWP and (b) land use for all model scenarios. Error bars show variance over all building construction cutoff years.

Figure 4b shows the change in land use for the four scenarios. In all cases UF led to net increases in land occupation. The Land(+) optimization minimized these to 57% of those from the GWP(+) scenario (1033 vs. 1786 acres/a increase). Akin to the GWP results, land use for both optimization scenarios approached each other using the upper bound of UF space (~6400 acre/a increase). In the context of Boston’s total food-related land occupation, these increases were a mere 0.07-0.5%, and although hinting at UF's potential to worsen a city's environmental performance, are not reason to outright discount UF as a food source for Boston. Land use increases stemmed from the low-yield, ground-based UF which is the dominant farm type in the model. Whilst UF frees some land beyond city boundaries, the practice requires more land within city borders to produce an equivalent volume, highlighting the comparative advantage of conventional production. Although already appropriated from the wild and hence imparting low ecological 'costs' in converting to UF, it is worth considering whether vacant urban land is best utilized for UF when solar farms net significantly greater environmental benefits per unit area, particularly for GHG reductions[21], but this could change in regions with lower GHG grid intensities (the Northeast US is primarily fossil fuel supplied). Rooftop UF performed quite well compared to conventional agriculture (exceptions being low yield vegetables where embodied land use in capital is large), but the relatively small rooftop area cultivated was not enough to counteract increases from ground UF. Although UF increased food related land use, the conversion of urban space to farms could increase urban biodiversity[49,50] and contribute to green corridors through the city, potentially justifying the practice.

UF impacts on Boston's energy and material metabolism

Naturally, the more buildings employed for UF, the larger the building energy related GWP reductions in Boston. In the Land(+) scenario, building energy savings accounted for 19% and 1% of total GWP reductions to the city using 1900 and 2000 as construction cutoffs, respectively, compared to 17% and 1% for the GWP(+) simulations. Both optimizations resulted in approximately the same building energy GWP reductions (3.2×10^6 kg CO_2e), but they took on increased importance for the land optimization due to its poorer GWP performance. When the simulations ran until Boston vegetable demands were met, building energy reductions contributed a maximum of 5% to total GWP reductions as building UF took on a diminished share of total production. In terms of contributions to total building energy demand, reduction from UF's was in the single digits. UF's potential urban heat island mitigation was excluded here, which could reduce ambient temperatures by 1-2° C[51], affecting cooling energy loading. However, cooling energy pales in comparison to heating demands in New England (1% and 59% of total residential end use, respectively in Massachusetts)[43,44], hinting at the limited ability of UF to affect baseline urban energy metabolism, although more detailed modeling is required.

Figures 5a-b outline UF's impacts on surface runoff and solid waste flows in Boston. Building space was highly influential on these interactions since it is the majority of UF area that shifts from non- to permeable and its significant compost needs due to soil losses and expanded shale grow-media devoid of nutrients[21]. Here we focus on building cutoff years of 1900 and 2000 (other years shown in the supplementary information graphics). Figure 4a shows that the GWP(+) and Land(+) simulations (averaged due to similarity) provided significantly greater runoff retention, since they were forced to use all available building area. The subtractive scenarios provided less runoff reduction as they favored ground UF when optimizing (particularly the GWP(+) scenario) and did not convert any impermeable area on the ground to UF. The maximum estimated runoff retention was 2.0 Mm^3/a, or 2.0% of annual stormwater (1.11 m annual precipitation falling on 67.8 km^2 impermeable area and 57.4 km^2 permeable with 50% assumed retention[49]).

Yard and kitchen solid waste assimilation as compost (also averaged for land and GWP optimizations) was highest for the subtractive scenarios (~12000 tons/a), decreasing as building space was removed to approximately 8200 tons/a by cutoff year 2000. Additive scenarios provided lower waste assimilation capacity (10648-4026 tons/a) and were more sensitive to building space removal as this constituted a larger proportion of UF area. By our estimates UF could absorb at most 9% of Boston's municipal organic solid waste fraction at 2009 generation rates[52].

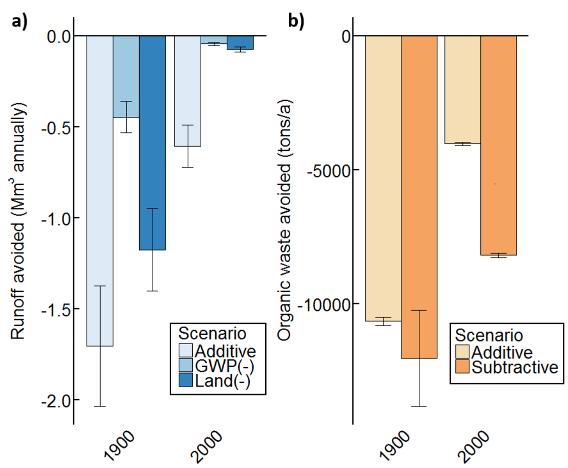

Figure 5a-b. Effects of UF on Boston's material metabolism for (a) runoff and (b) organic solid waste uptake for cutoff years 1900 and 2000. Error bars display range for high and low retention values for the runoff and variance over 100 Monte Carlo simulations for waste uptake.

Alternative motives for UF

Given UF's meager improvements in food related GWP and potential exacerbation of land use impacts, urban designers in the Northeast US should reconsider their enthusiasm for UF as a component of an environmentally sustainable urban food system, especially compared to higher environmental gains from other land applications[21]. Urban farms in the region do not tackle the animal-sourced foods that drive dietary environmental burdens. Other cities in the Global North are actively promoting reduced meat intake as explicit environmental initiatives, recognizing the importance of diet, and not technology, as means to more sustainable cities[53,54]. In a US context, shifting from average to vegetarian and vegan diets would reduce GWP by 30% and 50%, respectively[39] and reduce land use by a factor two or greater[47].

Effects of UF on Boston's building energy demands and surface runoff were both meagre, though the latter's ability to stymie sewage overflow events during heavy rains is notable[55]. UF incorporated a sizeable amount of organic solid waste, although meaningful shifts towards a circular metabolism should tackle wastewater management systems, where most imported nutrients end up[56,57].

Notwithstanding, UF is also often promoted as a social enterprise in the US Northeast[7]. The slight environmental gains should be compared against performance in other domains to see if current policies are justified given alternative motivations. In Boston, a significant percentage of residents do not meet recommended fruit and vegetable guidelines, and some of the city's neighborhoods have elevated poverty rates[58]. Here we test UF's potential contributions towards alleviating these challenges.

Nutritional Improvements

UF's nutritional contributions were assessed as the percentage of USDA recommended annual vegetable intake met for the three vegetable types grown by our case farms: 'dark green' (e.g. spinach, kale, broccoli), 'red and orange' (tomatoes, carrots, squash) and 'other' (lettuce, onions, cucumbers)[59]. USDA guidelines for these vegetable types at different ages and sexes were combined with census data to calculate Boston's total vegetable needs. We estimated that Boston currently consumes 64%, 64% and 85% of its dark green, red/orange and other vegetable needs, respectively (see Table S47 in the supplementary information). Nutrition optimization algorithms were run for both additive (+) and subtractive (-) grow area estimates, where the farms supplied equal nutritional requirements for each vegetable type.

Figure 6 shows average nutritional output for the previous scenarios and nutrition optimizations. Both GWP and land optimizations provided appreciable percentages of red/orange and other vegetable needs, but dark greens were not produced in volumes greater than 11% of recommended intakes. The Nutrition(+) optimization reduced red/orange and other vegetable production, but provided a fourfold jump in dark green cultivation, while the Nutrition(-) scenario supplied all of Boston's needs in the three categories.

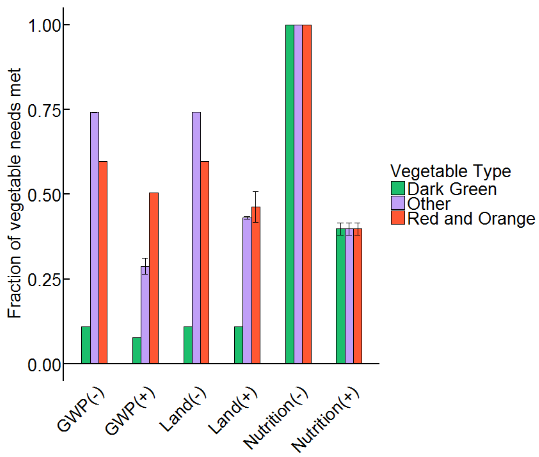

Figure 6. Fraction of vegetable needs met by UF in Boston for the different scenarios according to USDA dietary guidelines.

In terms of GWP reduction the nutritional scenario was similar to the Land(+) simulation (15726±733 tons CO_2e/a) and provided the largest reductions of all scenarios when producing until all nutritional needs were assuaged (39312±25 tons CO_2e/a or 2.9% of average dietary GWP), since it substituted the greatest volume of conventional produce. When producing to meet all nutritional demands, land use impacts were reduced relative to the other optimizations (3746±77 acres/a), since the Nutrition(-) scenario grew significantly more dark green vegetables, which provide high marginal land use reductions. The scale of interactions with the city remained largely unchanged, but the Nutrition(-) scenario had 25% greater solid waste assimilation capacity since cultivated area was the largest of all scenarios.

We also tested when UF acts as an *ancillary food supply* that can be used to alleviate the aforementioned gaps between USDA guidelines and current consumption. As UF would not substitute conventional produce here, no crediting was provided to the city and full burdens of UF production were ascribed to Boston. By our estimates Boston could actually close its nutritional gap for these food groups within the UF space estimated by the additive method, with the downside of increasing land use by 2608$\pm$89 acres/a (0.2%) and GWP by 2950$\pm$138 tons CO_2e/a (0.2%). However, the ecological costs should be weighed against the benefits of closing nutritional gaps, particularly in inner city neighborhoods bereft of fresh vegetable choices where lifestyle related diseases are more prominent[60,61]. Nutritional gaps would remain for other vegetable types ('starchy' and 'legumes') and fruits, but promoting UF as a public health measure appears justified.

Economic benefits

Lastly we looked at the ability for UF to provide economic returns to the block-groups for all of the GWP, land and nutritional optimization scenarios. Because supplying Boston's vegetable demands or nutritional needs required ~50% and 64% of total UF area, respectively, we also explored Boston's potential to export beyond its borders to the larger metropolitan area. Vegetable prices were taken US Bureau of Labor Statistics and USDA data[62,63]. The 191 acres of UF applied to surface parking in the additive scenarios were removed here, since this area already generates revenue.

Figure 7a shows that when restricted to intra-block-group trading, estimated UF market value was lowest (~1.5×10^7 USD) for the GWP(-) and Land(-) trials, as more block-groups were self-sufficient. Market value for internal trading is maximized (~4.9×10^7 USD) when the model aimed to meet its nutritional needs, as this left the most block-groups in production deficits, necessitating purchases from block-groups with surplus production capacity. Figure 7b shows an estimated market value of ~1.6×10^{8} USD when the city used all UF space, with exports to the metropolitan region accounting for ~90% of that when producing to meet current vegetable *demands* and dropping to 67% when satisfying nutritional *needs*. Situating this within the Boston-Cambridge-Newton metropolitan area, estimated UF market value amounted to less than 0.5% of regional GDP[64]. Notwithstanding, Figure 7c maps potential UF revenue in the Nutrition(-) scenario along with household poverty rates in Boston, demonstrating UF as a latent revenue stream to some of Boston's impoverished neighborhoods. ~$2.5*10^{7}$ USD could be generated in low income block-groups housing ~81 thousand residents (1/3 of Boston's residents in low income blocks). However, most of the market value (~$1.0*10^{8}$ USD) would benefit blocks with poverty rates below 25%.

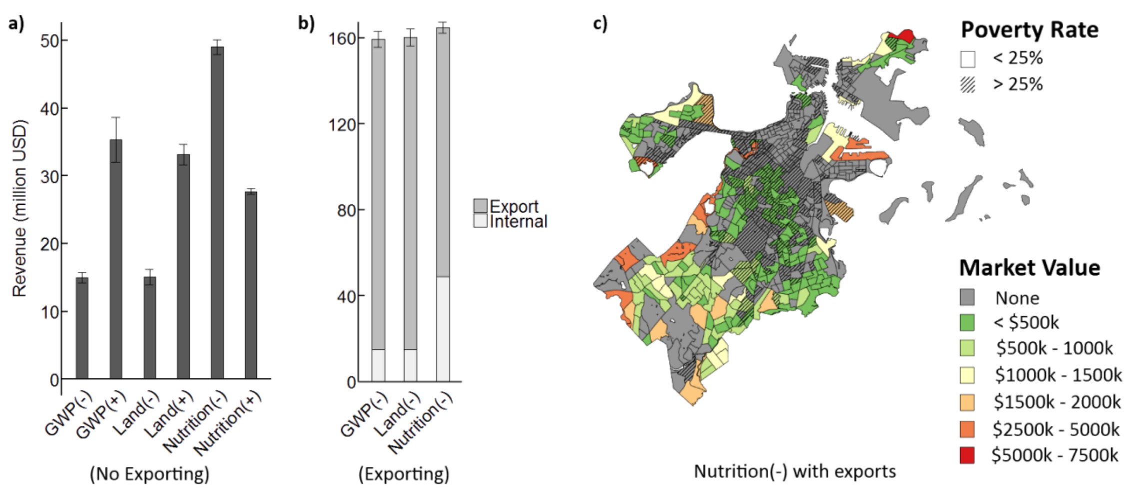

Figure 7a-c. Potential UF revenue in Boston when (a) limited to intra-block-group trading and (b) exports outside of city allowed. (c) Revenue production (with exporting) in block-groups after supplying cities nutritional needs with household poverty rates overlaid.

UF and study challenges

One challenge to the diffusion of UF into the city is pollution in soil and groundwater, as well as aerial deposition of contaminants from the concentration of industry and traffic in urban areas[65,66]. Of particular concern is the legacy of lead in soil from lead-containing fossil fuel combustion, although minimal uptake outside of the root zone occurs, and oral intake can be obviated through discarding of root portions and proper rinsing of edible portions[67]. Polycyclic aromatic hydrocarbons pose a similar issue, more so from aerial deposition than plant uptake, and can usually be made safe for consumption by rinsing edible portions[67]. Actual ingestion of toxic substances through UF remains understudied, and is a serious concern despite these positive signs. The presence of contamination is site specific, but it is correlated to age and density of the city[66], and in Northeast US cities the amount of current UF suitable area is certainly lower than our estimates.

UF is also at odds with other more economically competitive land uses that are usually preferred by municipal governments, further reducing long term production capacity[68]. Securing UF's role as a nutrition source in the Northeast US will likely require more than making the practice legal, but active protection of UF suitable space to avoid transitory UF application. This could easily be done for city-owned vacant properties as a start.

By including potentially contaminated land in our models this study represents an optimistic take on the potential for UF to affect a city's environmental performance. At the same time, using process-based LCA for crop production may have underestimated the burdens of both UF and substituted vegetables due to inventory gaps, depressing or inflating UF substitution effects. Furthermore, UF practice is constantly evolving, with improvements to current systems and new systems entering the market[17]. Although previous work has demonstrated that technologically advanced urban farms in the study region are the most burdensome due to energy impacts[21], future developments might shift the balance in the opposite direction. Our findings are only a snapshot of the current best-practices in the study region, which should be reevaluated as UF technology and the region's electrical grid mix evolve. However, given the marginal impacts of UF in this study, such shifts need to be seismic in order for UF contribution meaningfully to making Northeast US urban food consumption more environmentally sustainable.

Results should also be viewed in light of Boston's relatively dense built form, which produces high competition for the scarce open space remaining, reducing UF's tenability in the city and its environmental and nutritional impacts. Less-dense or warmer Northeast US cities may have greater production capacities per capita and resultant UF benefits, requiring care in directly applying our results directly to other Northeast US cities. A more complete assessment of local farming would look beyond political boundaries, including low-density suburbs and peri-urban regions where higher production volumes are possible[14,19]. Regional food system strategies, such as Vancouver, Canada's[69], could help distinct political entities coordinate their disparate land use regimes to maximize production and more effectively harness residual resources, increasing local farming's benefits. Although focusing on Boston's geopolitical boundaries precluded such a regional perspective, this study reveals the current limits of a lone, urban municipality to reduce the environmental burdens of its food demands through technology.

Despite these methodological challenges, we have shown that when embedded within a complex city system, UF's environmental performance is more nuanced than the previous studies at the farm scale or using hypothetical UF data at the city scale would suggest. We have demonstrated that it cannot be assumed that UF by default results in leaner supply chains. Policy makers and other urban designers in the Northeast US will hopefully benefit from this and future work when considering UF as a sustainable design intervention in the region.

ABBREVIATIONS

CO_2e, carbon dioxide equivalents; UF, urban farming; USDA, United States Department of Agriculture; NHANES, National Health and Nutrition Examination Survey; MRIO, multi-region-input-output; LCA, life cycle assessment; GWP, global warming potential.

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Supporting Information Available

Background data for the development of the food borne environmental footprints. Description of methods for urban agriculture area estimates, urban agriculture life cycle assessment and algorithms for urban farming proliferation in the city. Raw results from the models of impacts of urban farming in the city.

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Supplementary Information

Contributions of local farming to urban sustainability in the Northeastern United States

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Linking MRIO food impacts to different nutritional categories

As outlined in the article, ascribing the embodied impacts of from food consumption to different food products is done using kilo calories. The starting point of the assessment are the individual categories of nutrition as outlined by the United States Department of Agriculture's (USDA) 2015-2020 dietary guidelines[1].

USDA loss-adjusted food availability (LAFA) data[2] provide kilo calories per nutritional equivalent for individual foods within the broader nutritional categories (e.g. kcal of broccoli per cup equivalent of 'dark green vegetables'), which are then used to develop availability weighted averages of kilo calories per nutritional equivalent. Food losses are also included in the weighted average, so that the kilo calories per nutritional unit approximate the amount of kilo calories provided by the economy for consumption and not just those actually consumed. Tables S1-19 outline the calculations of embodied kilo calories in the nutritional group.

Table S1 - Vegetables: Dark Green

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily	Food pattern equivalents available daily	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number -*	*-- Cups --*	*kcal*	*kcal produced/cup consumed*
Fresh broccoli	12	39	12	0.947	0.031	2.195	71.855
Fresh collard greens	37	43	38	0.029	0.002	0.248	100.999
Fresh escarole	48	14	24	0.030	0.004	0.092	24.664
Fresh kale	39	39	38	0.022	0.001	0.154	200.145
Fresh leaf lettuce	14	21	24	0.995	0.077	2.089	27.290
Fresh mustard greens	64	7	38	0.023	0.002	0.116	75.014
Fresh spinach	14	28	9	0.222	0.016	0.412	25.959
Fresh turnip greens	41	30	38	0.031	0.002	0.164	95.294
Frozen broccoli	6	-	12	0.585	0.011	0.707	62.863
Frozen spinach	6	-	34	0.131	0.002	0.212	104.771
						Weighted Average:	43.617

Table S2 – Vegetables: Other

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily	Food pattern equivalents available daily	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number -*	*-- Cups --*	*kcal*	*kcal produced/cup consumed*
Fresh artichokes	19	60	18	0.149	0.002	0.840	428.102
Fresh asparagus	9	47	18	0.084	0.003	0.264	85.157
Fresh green bell pepper	8	18	39	0.427	0.014	1.078	75.645
Fresh Brussels sprouts	19	10	12	0.094	0.002	0.149	59.965
Fresh cabbage	14	20	24	1.093	0.050	2.271	45.721
Fresh cauliflower	14	61	9	0.125	0.005	0.485	104.660
Fresh celery	5	11	39	0.546	0.034	1.151	33.721
Fresh cucumbers	6	27	32	0.332	0.024	0.864	36.376
Fresh eggplant	21	19	26	0.101	0.005	0.233	46.222
Fresh garlic	7	13	43	1.665	0.008	4.087	498.354
Fresh head lettuce	9	16	24	1.557	0.097	2.843	29.216
Fresh mushrooms	13	3	21	0.421	0.020	0.634	31.651
Fresh okra	24	14	20	0.081	0.002	0.163	66.153
Canned olives	6	0	25	2.126	0.014	3.016	219.858
Fresh onions	10	10	43	4.283	0.067	10.099	150.892
Fresh radishes	21	10	47	0.035	0.002	0.102	55.947
Fresh snap beans	19	12	24	0.415	0.013	0.796	59.478
Fresh squash	12	17	25	0.373	0.021	0.735	35.456
Canned asparagus	6	0	2	0.026	0.001	0.028	49.935
Canned snap beans	6	0	24	0.416	0.014	0.582	41.993
Canned cabbage	6	0	16	0.083	0.003	0.105	34.195
Canned cucumbers	6	0	3	0.876	0.011	0.960	89.384
Canned mushrooms	6	0	9	0.250	0.006	0.292	45.593
Frozen asparagus	6	0	26	0.007	0.000	0.011	46.003
Frozen snap beans	6	0	24	0.444	0.012	0.622	53.191
Frozen cauliflower	6	0	27	0.041	0.001	0.060	49.548
Dehydrated onions	6	0	4	0.442	0.005	0.490	108.599
Fresh avocados	9	26	32	2.516	0.011	6.607	622.305
						Weighted Average	88.607

Table S3 – Vegetables: Red and Orange

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily	Food pattern equivalents available daily	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number -*	*-- Cups --*	*kcal*	*kcal produced/cup consumed*
Fresh red bell pepper	8	18	39	0.427	0.014	1.077	75.644
Fresh carrots	5	11	34	2.056	0.039	3.942	99.668
Fresh pumpkin	11	30	69	0.012	0.001	1.436	3379.731
Fresh tomatoes	13	9	7	3.370	0.082	4.621	56.220
Canned carrots	6	0	31	0.136	0.003	0.210	55.504
Canned chili peppers	6	0	4	1.022	0.035	1.132	32.136
Canned tomatoes	6	0	28	3.750	0.098	5.541	56.146
Other canned vegetables	6	0	16	0.503	0.010	0.637	62.056
Frozen carrots	6	0	34	0.236	0.004	0.381	87.040
						Weighted Average	66.720

Table S4 – Vegetables: Starchy

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily	Food pattern equivalents available daily	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number --*	*-- Cups --*	*kcal*	*kcal produced/cup consumed*
Fresh sweet corn	1	64	32	0.361	0.003	9.091	3144.228
Fresh potatoes	6	10	16	28.391	0.229	41.031	178.492
Fresh sweet potatoes	14	28	44	1.172	0.010	4.879	474.417

Canned sweet corn	6	0	7	3.642	0.033	4.166	125.829
Canned green peas	6	0	24	0.476	0.004	0.666	166.573
Canned potatoes	6	0	28	0.314	0.003	0.465	159.574
Frozen sweet corn	6	0	36	1.638	0.012	2.722	222.739
Frozen green peas	6	0	24	1.167	0.009	1.634	174.972
Frozen lima beans	6	0	27	0.293	0.001	0.427	275.429
Frozen potatoes	6	0	16	20.345	0.143	25.761	179.837
Misc. frozen vegetables	6	0	26	0.787	0.009	1.132	113.858
Dehydrated potatoes	6	0	4	7.227	0.068	8.008	117.464
Potato chips	6	0	4	28.465	0.186	31.544	169.547
Dry lima beans	6	0	10	0.118	0.002	0.139	63.829
						Weighted Average	183.947

Table S5. Fruits – Citrus

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily	Food pattern equivalents available daily	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number --*	*-- Cups --*	*kcal*	*kcal produced/cup consumed*
Fresh oranges	12	27	36	1.382	0.016	4.225	261.314
Fresh tangerines	20	26	52	0.279	0.003	1.595	588.447
Fresh grapefruit	13	50	20	0.286	0.003	1.095	313.588
Fresh lemons	7	47	44	0.081	0.001	0.964	728.504
Fresh limes	8	16	44	0.293	0.015	0.800	54.536
Fresh blueberries	5	5	8	0.314	0.004	0.380	101.898
Fresh cranberries	6	2	26	0.038	0.001	0.055	75.332
Fresh honeydew	23	54	43	0.017	0.000	0.754	2697.253
Fresh kiwi	13	14	45	0.108	0.001	0.302	212.224
Fresh raspberries	10	4	20	0.074	0.001	0.108	93.312
Fresh strawberries	10	6	35	1.220	0.025	2.291	92.591
Fresh watermelon	17	48	13	1.573	0.034	4.845	141.727
Frozen blackberries	6	0	40	0.042	0.000	0.074	171.986
Frozen raspberries	6	0	24	0.191	0.003	0.268	102.184
Frozen strawberries	6	0	24	0.151	0.003	0.211	72.788
Frozen other berries	6	0	30	0.023	0.000	0.035	147.416
						Weighted Average	162.457

Table S6. Fruits - Juice

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily[4]	Food pattern equivalents available daily[5]	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number --*	*-- Cups --*	*kcal*	*kcal produced/cup consumed*
Orange juice	6	0	10	18.071	0.161	21.361	132.388
Grapefruit juice	6	0	10	1.252	0.013	1.480	113.475
Lemon juice	6	0	10	0.283	0.005	0.335	63.830
Lime juice	6	0	10	0.050	0.001	0.059	70.922
Apple juice	6	0	10	9.712	0.085	11.480	134.752
Cranberry juice	6	0	10	0.990	0.009	1.170	137.116
Grape juice	6	0	10	3.163	0.021	3.739	179.669
Pineapple juice	6	0	10	1.055	0.008	1.247	156.028
Prune juice	6	0	32	0.223	0.001	0.349	284.731
						Weighted Average	135.490

Table S7. Fruits: Other

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily[4]	Food pattern equivalents available daily[5]	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number --*	*-- Cups --*	*kcal*	*kcal produced/cup consumed*
Fresh apples	9	10	20	6.597	0.118	10.314	87.546
Fresh apricots	35	7	10	0.045	0.001	0.084	141.924
Fresh bananas	8	36	20	11.644	0.091	28.754	314.855
Fresh cantaloupe	12	49	43	0.261	0.005	3.716	804.376
Fresh cherries	4	9	51	0.294	0.003	0.766	221.060
Fresh grapes	8	4	33	3.670	0.035	6.303	178.627
Fresh mangoes	14	31	13	0.714	0.007	1.490	206.683
Fresh papaya	55	33	20	0.116	0.002	0.547	292.434
Fresh peaches	12	7	42	1.045	0.016	2.326	146.909
Fresh pears	18	10	20	1.209	0.013	2.095	156.860
Fresh pineapple	15	49	37	0.352	0.004	2.945	686.082
Fresh plums	17	6	27	0.304	0.004	0.548	137.189
Canned apples	6	0	8	2.210	0.022	2.555	117.946
Canned apricots	6	0	27	0.032	0.001	0.046	72.865
Canned sweet cherries	6	0	32	0.006	0.000	0.010	178.348
Canned tart cherries	6	0	32	0.051	0.001	0.079	137.672
Canned peaches	6	0	9	1.176	0.020	1.374	68.974
Canned pears	6	0	9	1.099	0.015	1.285	83.002
Canned pineapple	6	0	9	1.335	0.017	1.561	92.354
Canned plums	6	0	26	0.007	0.000	0.011	146.636
Frozen blueberries	6	0	29	0.158	0.002	0.237	118.370
Frozen sweet cherries	6	0	29	0.149	0.001	0.223	346.119
Frozen tart cherries	6	0	29	0.187	0.003	0.280	106.383
Frozen apples	6	0	35	0.195	0.002	0.320	135.843
Frozen apricots	6	0	35	0.015	0.000	0.025	135.843
Frozen peaches	6	0	35	0.258	0.003	0.422	135.843
Frozen plums	6	0	10	0.002	0.000	0.002	98.109
Dried apples	6	0	11	0.287	0.003	0.343	124.313
Dried apricots	6	0	11	0.312	0.002	0.373	187.664
Dried dates	6	10	25	0.265	0.001	0.434	338.789
Dried figs	6	0	25	0.203	0.001	0.288	263.830
Dried peaches	6	0	11	0.118	0.001	0.141	228.305
Dried plums	6	0	11	0.732	0.004	0.875	249.821
Raisins	6	0	26	3.653	0.017	5.252	311.961

Weighted Average	183.640

Table S8. Grains

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily[4]	Food pattern equivalents available daily[5]	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number --*	*Oz*	*kcal*	*kcal produced/Oz consumed*
White and whole wheat flour	12	0	20	376.435	4.591	534.709	116.477
Rye flour	12	0	20	2.152	0.027	3.056	113.636
Rice	12	0	33	54.012	0.524	91.607	174.695
Corn flour and meal	12	0	20	60.937	0.952	86.558	90.909
Corn hominy and grits	12	0	20	28.810	0.389	40.923	105.114
Corn starch	12	0	20	11.548	0.241	16.404	68.182
Barley products	12	20	14	1.716	0.017	2.955	172.176
Oat products	12	20	14	12.920	0.121	22.246	184.229
Durum flour	12	0	20	40.140	0.379	57.018	150.568
						Weighted Average	118.150

Table S9. Dairy - Cheese

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily[4]	Food pattern equivalents available daily[5]	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number --*	*Cup*	*kcal*	*kcal produced/cup consumed*
Cheddar cheese	6	0	11	42.890	0.248	51.267	206.789
Other American cheese	6	0	28	8.707	0.053	12.866	241.578
Provolone cheese	6	0	14	3.751	0.025	4.640	184.315
Romano cheese	6	0	8	1.154	0.007	1.335	190.796
Parmesan cheese	6	0	8	2.818	0.016	3.258	206.984
Mozzarella cheese	6	0	31	25.454	0.204	39.245	192.414
Ricotta cheese	6	0	12	1.384	0.007	1.673	233.922
Other Italian cheese	6	0	16	0.671	0.004	0.850	205.547
Swiss cheese	6	0	50	2.803	0.017	5.965	344.681
Brick cheese	6	0	40	0.063	0.000	0.111	280.142
Muenster cheese	6	0	35	0.933	0.006	1.526	255.319
Blue cheese	6	0	43	0.678	0.005	1.266	279.955
Other miscellaneous cheese	6	0	42	3.554	0.023	6.519	287.417
Regular cottage cheese	12	0	31	0.705	0.002	1.162	602.767
Low-fat cottage cheese	12	0	4	1.063	0.003	1.259	384.706
						Weighted Average	214.276

Table S10. Dairy - Milk

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily[4]	Food pattern equivalents available daily[5]	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number --*	*Cup*	*kcal*	*kcal produced/cup consumed*
Plain whole milk	12	0	20	28.079	0.188	39.885	211.648
2 percent milk	12	0	20	26.152	0.214	37.148	173.295
1 percent milk	12	0	20	8.044	0.079	11.426	144.886
Skim milk	12	0	20	8.050	0.097	11.435	117.898
Whole flavored milk	12	0	45	1.096	0.005	2.264	429.752
Low-fat flavored milk	12	0	45	5.433	0.030	11.226	380.165
Buttermilk	12	0	18	0.603	0.006	0.836	135.809
Ice cream	12	0	24	24.519	0.060	36.661	613.038
Ice milk	12	0	24	8.826	0.022	13.197	613.038
Other frozen	12	0	33	4.895	0.021	8.303	388.399
Evap condensed canned whole milk	12	0	15	15.950	0.094	21.323	225.936
Evap condensed bulk whole milk	12	0	15	40.737	0.241	54.462	225.936
Evap condensed skim milk	12	0	15	4.289	0.043	5.733	133.690
Dry whole milk	1	0	41	0.562	0.004	0.962	272.214
Nonfat dry milk	1	0	41	7.366	0.068	12.610	186.612
Dry buttermilk	1	0	41	0.649	0.006	1.111	198.596
Eggnog	12	0	51	0.044	0.000	0.101	347.866
						Weighted Average	228.156

Table S11. Dairy - Yoghurt

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily[4]	Food pattern equivalents available daily[5]	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number --*	*Cup*	*kcal*	*kcal produced/cup consumed*
Yoghurt	12	0	21	5.804	0.041	8.349	205.696

Table S12. Protein – Eggs

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily[4]	Food pattern equivalents available daily[5]	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number --*	*Oz*	*kcal*	*kcal produced/Oz consumed*
Eggs	9	12	13	37.843	0.485	63.978	131.868

Table S13. Protein - Legumes

	Loss from retail/	Loss at consumer level	Kilo calories	Food pattern	Produced kilo	Calorific density

	Loss from retail/ institutional to consumer level	Loss at consumer level: Nonedible share	Loss at consumer level: Other (cooking loss and uneaten food)	Kilo calories available daily[4]	Food pattern equivalents available daily[5]	Produced kilo calories	Calorific density
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number --*	*Oz*	*kcal*	*kcal produced/Oz consumed*
Fresh lima beans	12	56	27	0.005	0.000	0.036	310.524
Dry Peas and lentils	6	0	10	0.317	0.007	0.375	56.865
Dry black beans	6	0	10	0.769	0.014	0.909	64.291
Dry great northern beans	6	0	10	0.334	0.007	0.395	57.460
Dry navy beans	6	0	10	1.450	0.025	1.714	68.246
Dry pinto beans	6	0	10	4.078	0.069	4.821	69.708
Dry red kidney beans	6	0	10	0.649	0.012	0.767	61.855
Other dry beans	6	0	10	1.806	0.033	2.134	65.581
						Weighted Average	66.797

Table S14. Protein - Meat

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily[4]	Food pattern equivalents available daily[5]	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number --*	*Oz*	*kcal*	*kcal produced/Oz consumed*
Beef	4	0	20	170.871	2.084	223.290	107.155
Veal	25	0	20	0.557	0.009	0.934	108.934
Pork	4	0	29	94.164	1.405	138.666	98.665
Lamb	12	0	20	2.140	0.026	3.050	118.300
						Weighted Average	103.855

Table S15. Protein - Poultry

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily[4]	Food pattern equivalents available daily[5]	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number --*	*Oz*	*kcal*	*kcal produced/Oz consumed*
Chicken	4	0	15	141.470	2.143	173.318	80.858
Turkey	3	0	35	20.498	0.380	32.666	86.055
						Weighted Average	81.640

Table S16. Protein - Nuts

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily[4]	Food pattern equivalents available daily[5]	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number --*	*Oz*	*kcal*	*kcal produced/Oz consumed*
Peanuts	6	0	4	40.179	0.502	44.524	88.652
Almonds	6	0	21	6.518	0.079	8.777	110.423
Hazelnuts	6	0	20	0.296	0.003	0.394	118.351
Pecans	6	0	14	3.095	0.032	3.828	121.227
Walnuts	6	0	18	2.999	0.032	3.890	120.654
Macadamia	6	0	8	0.835	0.008	0.965	117.946
Pistachios	6	0	16	1.267	0.016	1.605	101.317
Other tree nuts	6	0	18	6.525	0.073	8.466	116.373
						Weighted Average	97.164

Table S17. Protein - Fish and Seafood

	Loss from retail/ institutional to consumer level	Loss at consumer level		Kilo calories available daily[4]	Food pattern equivalents available daily[5]	Produced kilo calories	Calorific density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	*-- Number --*	*Oz*	*kcal*	*kcal produced/Oz consumed*
Fresh and frozen fish	9	0	40	5.598	0.158	10.218	64.802
Fresh and frozen shellfish	9	0	40	3.265	0.131	5.998	45.925
Canned Salmon	6	0	17	0.406	0.010	0.521	49.987
Canned Sardines	6	0	36	0.304	0.005	0.505	98.072
Canned Tuna	6	0	17	3.035	0.092	3.889	42.297
Canned shellfish	6	0	17	0.419	0.015	0.536	35.888
Other canned fish	6	0	17	0.402	0.010	0.515	49.987
Cured fish	6	0	17	0.336	0.010	0.431	42.297
						Weighted Average	52.438

Table S18. Fats and Oils

	Loss from retail/ institutional to consumer level	Loss at consumer level		Energy content	Per capita availability adjusted for loss	Per capita availability adjusted for loss	Calorific Density
		Nonedible share	Other (cooking loss and uneaten food)				
Component	-- Percent --	-- Percent --	-- Percent --	kcal/g	g/d	kcal/d	kcal produced/g consumed
Butter	7	0	35	9	2.815	25.333	14.888
Margarine	7	0	35	9	2.037	18.335	14.888
Lard	50	0	35	9	0.651	5.858	27.692
Edible beef tallow	50	0	35	9	1.189	10.705	27.692
Shortening	21	0	35	9	13.368	120.316	17.527
Salad and cooking oils	21	0	15	9	41.885	376.969	13.403
Other edible fats and oils	5	0	25	9	1.488	13.388	12.632
Light cream	12	0	12	9	1.556	14.000	11.622
Sour cream	12	0	8	9	0.819	7.371	11.117
Cream cheese	12	0	13	9	0.744	6.695	11.755
Eggnog	12	0	51	9	0.011	0.098	20.872

Weighted Average	14.630

Table S19. Sugars							
		Loss at consumer level					
	Loss from retail/ institutional to consumer level	Nonedible share	Other (cooking loss and uneaten food)	Energy content	Per capita availability adjusted for loss	Per capita availability adjusted for loss	Calorific Density
Component	*-- Percent --*	*-- Percent --*	*-- Percent --*	kcal/g	kcal/d	kcal/d	kcal produced/kcal consumed
Cane and beet sugar	11	0	34	-	169.976	289.370	1.702
Edible syrups	11	0	15	-	2.221	2.936	1.322
Honey	11	0	15	-	3.340	4.415	1.322
High fructose corn sweetener	11	0	34	-	155.278	264.349	1.702
Glucose	11	0	34	-	38.070	64.811	1.702
Dextrose	11	0	34	-	8.256	14.056	1.702
						Weighted Average	1.697

We take the average US usual daily food intake for each nutritional group over the years 2007-2010 (in cup equivalents, ounce equivalents, etc) from the National Nutritional Health and Nutrition Examination Survey (NHANES)[3] and multiply this by the population (301,231,207) and kilo calories per serving nutritional component to arrive at the total calorific demand of the US population. Table S20 outlines these findings.

Table S20. US average per capita food equivalent, daily calorific and annual calorific intake (2007-2010)					
Dietary Component	**NHANES Usual Daily Intake**	**Unit**	**kcal produced per nutritional equivalent**	**Daily per capita kcal**	**Annual per capita kcal**
Vegetables					
Dark Green	0.1	cup eq.	43.61664	4.36166418	1592.007427
Red and Orange	0.4	cup eq.	65.72036	26.2881426	9595.172043
Other	0.5	cup eq.	88.60711	44.3035567	16170.79821
Starchy	0.4	cup eq.	183.9475	73.5789929	26856.33242
Fruits					
Citrus	0.2	cup eq.	162.4571	32.4914191	11859.36796
Juice	0.4	cup eq.	135.4902	54.1960631	19781.56303
Other	0.5	cup eq.	183.6407	91.8203589	33514.431
Grains					
Total	6.3	Oz eq.	118.1499	744.344173	271685.6231
Dairy					
Milk	1	cup eq.	228.1564	228.156392	83277.083
Cheese	0.7	cup eq.	214.2764	149.99351	54747.6311
Yoghurt	0.1	cup eq.	205.6962	20.5696203	7507.911392
Protein					
Meat	2.5	Oz eq.	103.8546	259.636553	94767.34176
Poultry	1.5	Oz eq.	81.64011	122.46017	44697.96204
Eggs	0.5	Oz eq.	131.8681	65.9340659	24065.93407
Legumes	0.5	Oz eq.	66.79709	33.3985472	12190.46974
Nuts	0.6	Oz eq.	97.16419	58.2985134	21278.9574
Seafood	0.5	Oz eq.	52.43769	26.2188457	9569.878694
Fats and Oils					
Total	56.8	g	14.63028	830.99974	303314.905
Sugars					
Total	268	kcal	1.696806	454.744058	165981.5812
Beverages					
Total*	-	-	-	447	163230

* NHANES does not overtly track the kilo calories consumed through beverages. Estimated here as the difference between the US average total available kilo calories daily according to LAFA data for 2010[2] (3769 kcal) and the sum of the food/juice intake estimated here.

Total GWP and land use impacts for US final demands were taken from the EXIOBASE v2.3 default final demand vector which represents consumption for the year 2007 (www.exiobase.eu). This only accounts for impacts for production, excluding final transport to the consumer. To account for transport impacts, the transport margins are taken from the EXIOBASE data for each product and multiplied by the final demands vector to generate the resulting final transport needs for each good in 2007 USD. The modal share is then taken from the United States Commodity Flow Survey for the year 2007[4] using best judgement to link EXIOBASE products to the commodity groups covered in the survey. Table S21 displays the transport margins and modal share for each EXIOBASE product we include.

Table S21. Transport margins and modal shares for EXIOBASE products					
EXIOBASE Code	**Transport Margin**	**Modal Share – Road**	**Modal Share - Rail**	**Modal Share - Water**	**Modal Share – Air**
Paddy rice	0.115998	0.488242	0.363942	0.147816	0
Wheat	0.09643	0.488242	0.363942	0.147816	0
Cereal grains nec	0.10418	0.488242	0.363942	0.147816	0
Vegetables, fruit, nuts	0.131523	0.913812	0.043094	0.043094	0
Oil seeds	0	0.913812	0.043094	0.043094	0
Sugar cane, sugar beet	0	0.913812	0.043094	0.043094	0
Crops nec	0	0.913812	0.043094	0.043094	0
Cattle	0.006992	1	0	0	0
Pigs	0	1	0	0	0
Poultry	0.034421	1	0	0	0
Meat animals nec	0	1	0	0	0
Animal products nec	0.026805	0.991251	0.005661	0.003088	0.004117
Raw milk	0	0.936752	0.063248	0	0
Fish and other fishing products; services incidental of fishing (05)	0.061087	1	0	0	0
Products of meat cattle	0.053237	1	0	0	0
Products of meat pigs	0.063048	1	0	0	0
Products of meat poultry	0.054744	1	0	0	0
Meat products nec	0.077171	1	0	0	0
products of Vegetable oils and fats	0.040329	0.972208	0.025695	0.002098	0.001049
Dairy products	0.07116	0.936752	0.063248	0	0
Processed rice	0.063115	0.969017	0.029915	0.001068	0
Sugar	0.065962	0.972208	0.025695	0.002098	0.001049
Food products nec	0.077061	0.972208	0.025695	0.002098	0.001049
Beverages	0.101754	0.966173	0.033827	0	0
Fish products	0.08422	1	0	0	0

All transport is modeled using GWP and land use intensities for the US economy. The transport processes used here and their environmental intensities as taken from EXIOBASE are shown in Table S22.

Table S22. GWP and land use intensities for different transport modes				
EXIOBASE Code	**Country**	**Mode**	**GWP Intensity (kg CO_2e/10^6 EUR)**	**Land Use Intensity (km^2/10^6 EUR)**
Railway transportation services	US	Rail	1412976.522	1.256751515

Other land transportation services	US	Truck	778740.6385	0.26280198
Sea and coastal water transportation services	US	Water	3476526.152	0.536899867
Air transport services	US	Air	2832246.05	0.309460771

Finally the MRIO calculations are performed; yielding the total production and transport related impacts related to US consumption for the year 2007. Table S23 outlines the results of the MRIO manipulations.

Table S23. EXIOBASE results for 2007 US final consumption

	Production		Transport	
EXIOBASE Code	**GWP (kg CO_2e)**	**Land Use (km^2)**	**GWP (kg CO_2e)**	**Land Use (km^2)**
Poultry	5822816965	22376.74	80842374	27.28191
Products of meat poultry	32860973488	89477.22	9.56E+08	322.5918
Cattle	588291879	1731.563	402182.3	0.135725
Products of meat cattle	149156495799	461445	8.89E+08	299.8428
Products of meat pigs	17356597166	71345.54	6.9E+08	232.879
Pigs	0	0	0	0
Fish and other fishing products; services incidental of fishing	1267172044	1974.987	54883840	18.52168
Fish products	3860016147	8001.427	2.19E+08	73.96871
Meat products nec	7465819719	15791	3.94E+08	132.8264
Animal products nec	5768762921	32870.85	1.03E+08	34.80589
Dairy products	50604671333	225524.6	1.73E+09	686.0962
Processed rice	1615329595	3673.16	32217730	11.78406
Paddy rice	188415433	874.5804	12077810	5.703473
Cereal grains nec	3150569995	14125.08	77873089	36.77381
Wheat	1849616004	15205.19	50254915	23.73175
Products of Vegetable oils and fats	8879027984	63894.03	1.13E+08	40.58251
Vegetables, fruit, nuts	32863666424	355058.8	4.14E+09	1424.003
Sugar	3131171454	10810.13	99482266	35.80383
Beverages	80757542526	231330.2	5.48E+09	2031.049
Crops nec	955989660	58753.4	0	0
Food products nec	270641831417	1194618	9.84E+09	3541.019

Allocating global warming potential (GWP) and land use impacts from the EXIOBASE is done through a concordance matrix matching nutritional groups to relevant product groups. Concordances are made based on the descriptions provided in the United Nations International Standard Industrial Classification of All Economic Activities classification codes[5]. The total impact from US final demand in 2007 in each relevant EXIOBASE product is divided amongst the kilo calories for all nutritional components ascribed to that product. Letting I_j represent the total impacts (production and transport) from final demand for EXIOBASE food product j, and C_i the total kilo calories produced of nutritional category i, then the impacts of the EXIOBASE product j attributed to supplying a single kilo calorie of nutritional category x, $i_{x,j}$, is given by equation (1), where the denominator is the sum of kilo calories from all nutritional categories linked to that EXIOBASE product.

(1) $i_{x,j} = \frac{I_j}{\sum_{i=1}^{n} C_i}$

A single nutritional category could be matched to multiple EXIOBASE products, and hence, embodied impact per kilo calorie delivered in a nutritional category, i_x, is the sum of the components from each EXIOBASE product assigned to it, according to (2).

(2) $i_x = \sum_{j=1}^{n} i_{x,j}$

Table S24 shows the concordance between different EXIOBASE products and the nutritional categories. Table S25 shows the embodied GWP and land use impacts per kilo calorie nutritional category produced.

Table S24. Concordance matrix between EXIOBASE products and nutritional categories

EXIOBASE Code	**USDA Nutritional Category**
Poultry	Poultry, Eggs
Products of meat poultry	Poultry
Cattle	Meat
Products of meat cattle	Meat
Products of meat pigs	Meat
Pigs	Meat
Fish and other fishing products; services incidental of fishing	Fish and Seafood
Fish products	Fish and Seafood
Meat products nec	Meat
Animal products nec	Poultry, Meat, Fish and Seafood, Milk, Cheese, Yoghurt, Eggs
Dairy products	Milk, Cheese, Yoghurt
Processed rice	Grains
Paddy rice	Grains
Cereal grains nec	Grains
Wheat	Grains
Products of Vegetable oils and fats	Fars and Oils
Vegetables, fruit, nuts	Dark Green Vegetables, Red and Orange Vegetables, Starchy Vegetables, Citrus Fruits, Juice, Other Fruits, Nuts
Sugar	Sugars
Beverages	Beverages, Milk, Juice
Crops nec	Other Vegetables, Starchy Vegetables
Food products nec	Dark Green Vegetables, Red and Orange Vegetables, Starchy Vegetables, Citrus Fruits, Juice, Other Fruits, Nuts, Poultry, Meat, Fish and Seafood, Milk, Cheese, Yoghurt, Eggs, Grains, Legumes, Sugars, Beverages

Table S25. GWP and land use impacts per kilo calorie produced

USDA Nutritional Category	**GWP (kg CO_2e/kcal produced) - production**	**GWP (kg CO_2e/ kcal produced) - transport**	**Land Use (km^2/ kcal produced) - production**	**Land Use (km^2/ kcal produced) - transport**
Poultry	0.003409	9.90E-05	1.09E-08	3.39E-11
Citrus, melons, berries	0.001418	0.00012	1.12E-08	4.18E-11
Other Fruits	0.001418	0.00012	1.12E-08	4.18E-11
Meat	0.006777	9.32E-05	2.23E-08	3.20E-11
Grains	0.000731	2.57E-05	3.27E-09	9.43E-12
Dark Greens	0.001418	0.00012	1.12E-08	4.18E-11
Yoghurt	0.001854	6.37E-05	8.31E-09	2.44E-11
Red and Orange	0.001418	0.00012	1.12E-08	4.18E-11
Sugars	0.00071	2.55E-05	3.08E-09	9.19E-12
Nuts	0.001418	0.00012	1.12E-08	4.18E-11
Cheese	0.001854	6.37E-05	8.31E-09	2.44E-11
Fish and Seafood	0.002473	0.000119	6.64E-09	4.07E-11

Juice	0.002417	0.000188	1.40E-08	6.70E-11
Beverages	0.001647	9.14E-05	5.72E-09	3.36E-11
Starchy	0.001491	0.00012	1.57E-08	4.18E-11
Legumes and Soy	0.000648	2.36E-05	2.86E-09	8.48E-12
Other Vegetables	0.001491	0.00012	1.57E-08	4.18E-11
Fats and Oils	0.000745	2.48E-05	3.56E-09	8.92E-12
Milk	0.002853	0.000132	1.12E-08	4.95E-11
Eggs	0.000987	2.85E-05	4.27E-09	1.01E-11

Determining food related GWP and land use impacts for Boston final consumption

Embodied kilo calories per nutritional serving (Tables S1-19) can be connected with the GWP and land use impacts per kilo calorie nutritional category delivered to market (Table S25) to estimate environmental pressure exerted by different levels of food consumption. We use the NHANES 2007-2010 usual daily intake data for different demographics and US census data to estimate Boston's food related environmental burdens for the year 2010.

Table S26 shows the usual daily intake for different population segments based on sex and age, which when multiplied by 365 provide estimates of annual food demands for US citizens. It should be noted that NHANES, being self-reported, is plagued by underreporting by participants, particularly in foods that have negative health stigmas attached to them (red meat, sugar, highly processed foods, etc.) and is considered at the lower end of food consumption estimates[6]. Notwithstanding the above shortcoming, NHANES provides the most comprehensive and consistent data for US food consumption, with the added benefit of recording including important demographics data, and is therefore chosen here to model Boston's consumption.

Table S26. Usual daily intake for different demographics from NHANES 2007-2010

		Males								**Females**							
		Age								**Age**							
Nutritional Category	**Unit**	1-3	4-8	9-13	14-18	19-30	31-50	51-70	71+	1-3	4-8	9-13	14-18	19-30	31-50	51-70	71+
Citrus	cup eq.	0.2	0.2	0.2	0.2	0.1	0.2	0.3	0.3	0.2	0.2	0.2	0.1	0.2	0.2	0.3	0.3
Other Fruits	cup eq.	0.6	0.6	0.5	0.4	0.4	0.5	0.6	0.7	0.6	0.5	0.5	0.4	0.4	0.5	0.7	0.7
Juice	cup eq.	0.7	0.5	0.4	0.4	0.4	0.3	0.3	0.4	0.7	0.4	0.4	0.3	0.4	0.2	0.3	0.4
Dark Greens	cup eq.	0	0	0	0.1	0.1	0.1	0.2	0.1	0	0	0	0.1	0.1	0.1	0.2	0.1
Red and Orange	cup eq.	0.2	0.3	0.3	0.4	0.5	0.5	0.4	0.4	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.4
Other	cup eq.	0.1	0.2	0.2	0.3	0.6	0.6	0.7	0.5	0.2	0.2	0.3	0.3	0.5	0.6	0.7	0.5
Starchy	cup eq.	0.2	0.3	0.4	0.4	0.5	0.5	0.6	0.5	0.2	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Grains	oz eq.	4.1	6.1	7.3	8.2	8.1	7.8	6.9	6	3.7	5.6	6.5	6.1	5.9	5.5	5.1	4.9
Milk	cup eq.	1.9	1.5	1.6	1.5	0.8	0.9	0.9	1.1	1.9	1.5	1.3	0.9	0.7	0.8	0.8	0.9
Cheese	cup eq.	0.4	0.6	0.8	1	1	0.9	0.7	0.4	0.4	0.6	0.6	0.7	0.7	0.6	0.5	0.3
Yoghurt	cup eq.	0.1	0.1	0	0	0.1	0	0.1	0	0.1	0.1	0	0	0.1	0.1	0.1	0.1
Meat	oz eq.	1.2	1.8	2.3	3.2	3.4	3.8	3.3	2.7	1.1	1.7	2	1.6	2.1	2.1	1.9	1.8
Poultry	oz eq.	0.9	1.1	1.5	1.8	2.2	1.9	1.8	1.1	0.8	1	1.2	1.6	1.5	1.4	1.3	1
Eggs	oz eq.	0.4	0.4	0.4	0.4	0.6	0.7	0.7	0.7	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5
Legumes	oz eq.	0.2	0.2	0.3	0.4	0.6	0.7	0.6	0.4	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.3
Nuts	oz eq.	0.3	0.4	0.5	0.4	0.5	0.8	0.9	0.7	0.2	0.3	0.4	0.3	0.4	0.6	0.7	0.5
Fish and Seafood	oz eq.	0.1	0.1	0.2	0.3	0.6	0.7	0.8	0.6	0.1	0.2	0.2	0.2	0.4	0.5	0.6	0.5
Fats and Oils	g	39.1	50.1	59.2	68	67.2	72.1	66.4	55.5	36.6	47	53.4	51.1	50.8	50.3	50.3	44.1
Added Sugars	kcal	9.4	15.7	21.5	24.6	23.5	20.5	16.5	14	8.4	14.3	17.8	17.5	16.7	15.1	12.5	10.9
Beverages*	-	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

* Lacking demographic data for beverage intake, all respondents are assumed to have the same daily calorific intake from beverages

To move from NHANES usual daily intake to annual environmental impacts for a nutritional category, Y_x, the usual daily intake for nutritional component x, UDI_x, is combined with the produced kilo calories per nutritional unit, $kcal_x$, and the impacts per kilo calorie supplied to the market, i_x, and corrected for the number of days in a year:

(3) $$Y_x = (UDI_x \times kcal_x \times i_x) \times 365$$

Tables S27 and S28 show food related GWP and land use impacts for different demographics, respectively.

Table S27. Food related GWP impacts for different demographics in CO_2e/a/cap

	Males								**Females**							
	Age								**Age**							
Nutritional Category	1-3	4-8	9-13	14-18	19-30	31-50	51-70	71+	1-3	4-8	9-13	14-18	19-30	31-50	51-70	71+
Poultry	91.4	111.7	152.4	182.9	223.5	193.0	182.9	111.7	81.3	101.6	121.9	162.5	152.4	142.2	132.1	101.6
Citrus	16.8	16.8	16.8	16.8	8.4	16.8	25.2	25.2	16.8	16.8	16.8	8.4	16.8	16.8	25.2	25.2
Fish and Seafood	4.7	4.7	9.5	14.2	28.4	33.1	37.9	28.4	4.7	9.5	9.5	9.5	18.9	23.7	28.4	23.7
Other Fruits	57.0	57.0	47.5	38.0	38.0	47.5	57.0	66.5	57.0	47.5	47.5	38.0	38.0	47.5	66.5	66.5
Meat	308.3	462.4	590.9	822.1	873.5	976.2	847.8	693.6	282.6	436.7	513.8	411.0	539.5	539.5	488.1	462.4
Grains	129.2	192.2	230.0	258.4	255.2	245.8	217.4	189.1	116.6	176.5	204.8	192.2	185.9	173.3	160.7	154.4
Dark Greens	0.0	0.0	0.0	2.3	2.3	2.3	4.5	2.3	0.0	0.0	0.0	2.3	2.3	2.3	4.5	2.3
Red and Orange	6.8	10.2	10.2	13.6	17.0	17.0	13.6	13.6	6.8	6.8	10.2	10.2	13.6	13.6	13.6	13.6
Sugars	4.1	6.9	9.5	10.8	10.3	9.0	7.3	6.2	3.7	6.3	7.8	7.7	7.3	6.6	5.5	4.8
Nuts	15.1	20.1	25.1	20.1	25.1	40.2	45.3	35.2	10.1	15.1	20.1	15.1	20.1	30.2	35.2	25.1
Milk	451.4	356.4	380.1	356.4	190.1	213.8	213.8	261.3	451.4	356.4	308.8	213.8	166.3	190.1	190.1	213.8
Cheese	58.0	87.0	116.0	145.0	145.0	130.5	101.5	58.0	58.0	87.0	87.0	101.5	101.5	87.0	72.5	43.5
Juice	83.7	59.8	47.8	47.8	47.8	35.9	35.9	47.8	83.7	47.8	47.8	35.9	47.8	23.9	35.9	47.8
Beverages	268.9	268.9	268.9	268.9	268.9	268.9	268.9	268.9	268.9	268.9	268.9	268.9	268.9	268.9	268.9	268.9
Fats and Oils	155.5	199.2	235.4	270.4	267.2	286.7	264.0	220.7	145.5	186.9	212.3	203.2	202.0	200.0	200.0	175.4
Legumes and Soy	3.2	3.2	4.7	6.3	9.5	11.1	9.5	6.3	3.2	3.2	4.7	4.7	6.3	7.9	7.9	4.7
Other Vegetables	4.8	9.6	9.6	14.5	28.9	28.9	33.8	24.1	9.6	9.6	14.5	14.5	24.1	28.9	33.8	24.1
Yoghurt	13.9	13.9	0.0	0.0	13.9	0.0	13.9	0.0	13.9	13.9	0.0	0.0	13.9	13.9	13.9	13.9
Starchy	20.0	30.0	40.0	40.0	50.1	50.1	60.1	50.1	20.0	30.0	40.0	40.0	40.0	40.0	40.0	40.0
Eggs	19.0	19.0	19.0	19.0	28.5	33.2	33.2	33.2	14.2	14.2	19.0	19.0	19.0	23.7	23.7	23.7
Transport	72.5	75.7	82.6	88.7	86.2	89.4	88.3	80.4	70.9	71.7	74.6	67.1	70.2	70.6	73.1	69.7
Total	1784.4	2004.8	2296.2	2636.2	2617.9	2729.5	2561.7	2222.7	1719.0	1906.4	2030.3	1825.6	1955.0	1950.8	1919.7	1805.3

Table S28. Food related land use for different demographics in km^2/a/capita

Nutritional Category	**Males**								**Females**							
	Age								**Age**							
	1-3	4-8	9-13	14-18	19-30	31-50	51-70	71+	1-3	4-8	9-13	14-18	19-30	31-50	51-70	71+
Poultry	0.000301	0.000368	0.000501	0.000602	0.000735	0.000635	0.000602	0.000368	0.000267	0.000334	0.000401	0.000535	0.000501	0.000468	0.000435	0.000334
Citrus	0.000156	0.000156	0.000156	0.000156	7.80E-05	0.000156	0.000234	0.000234	0.000156	0.000156	0.000156	7.80E-05	0.000156	0.000156	0.000234	0.000234
Fish and Seafood	1.34E-05	1.34E-05	2.67E-05	4.01E-05	8.02E-05	9.36E-05	0.000107	8.02E-05	1.34E-05	2.67E-05	2.67E-05	2.67E-05	5.35E-05	6.68E-05	8.02E-05	6.68E-05
Other Fruits	0.000529	0.000529	0.000441	0.000353	0.000353	0.000441	0.000529	0.000617	0.000529	0.000441	0.000441	0.000353	0.000353	0.000441	0.000617	0.000617
Meat	0.001007	0.00151	0.00193	0.002685	0.002853	0.003188	0.002769	0.002265	0.000923	0.001426	0.001678	0.001342	0.001762	0.001762	0.001594	0.00151
Grains	0.000666	0.000991	0.001186	0.001332	0.001316	0.001267	0.001121	0.000975	0.000601	0.00091	0.001056	0.000991	0.000958	0.000893	0.000829	0.000796
Dark Greens	0	0	0	2.09E-05	2.09E-05	2.09E-05	4.19E-05	2.09E-05	0	0	0	2.09E-05	2.09E-05	2.09E-05	4.19E-05	2.09E-05
Red and Orange	6.31E-05	9.47E-05	9.47E-05	0.000126	0.000158	0.000158	0.000126	0.000126	6.31E-05	6.31E-05	9.47E-05	9.47E-05	0.000126	0.000126	0.000126	0.000126
Sugars	1.79E-05	2.99E-05	4.10E-05	4.69E-05	4.48E-05	3.91E-05	3.14E-05	2.67E-05	1.60E-05	2.72E-05	3.39E-05	3.33E-05	3.18E-05	2.88E-05	2.38E-05	2.08E-05
Nuts	3.04E-05	4.06E-05	5.07E-05	4.06E-05	5.07E-05	8.12E-05	9.13E-05	7.10E-05	2.03E-05	3.04E-05	4.06E-05	3.04E-05	4.06E-05	6.09E-05	7.10E-05	5.07E-05
Milk	0.001767	0.001395	0.001488	0.001395	0.000744	0.000837	0.000837	0.001023	0.001767	0.001395	0.001209	0.000837	0.000651	0.000744	0.000744	0.000837
Cheese	0.00026	0.00039	0.00052	0.00065	0.00065	0.000585	0.000455	0.00026	0.00026	0.00039	0.00039	0.000455	0.000455	0.00039	0.000325	0.000195
Juice	0.000555	0.000396	0.000317	0.000317	0.000317	0.000238	0.000238	0.000317	0.000555	0.000317	0.000317	0.000238	0.000317	0.000158	0.000238	0.000317
Beverages	0.000934	0.000934	0.000934	0.000934	0.000934	0.000934	0.000934	0.000934	0.000934	0.000934	0.000934	0.000934	0.000934	0.000934	0.000934	0.000934

Fats and Oils	0.000742	0.000951	0.001124	0.001291	0.001276	0.001369	0.001261	0.001054	0.000695	0.000892	0.001014	0.00097	0.000964	0.000955	0.000955	0.000837
Legumes and Soy	1.40E-05	1.40E-05	2.09E-05	2.79E-05	4.19E-05	4.88E-05	4.19E-05	2.79E-05	1.40E-05	1.40E-05	2.09E-05	2.09E-05	2.79E-05	3.49E-05	3.49E-05	2.09E-05
Other Vegetables	4.26E-05	8.51E-05	8.51E-05	0.000128	0.000255	0.000255	0.000298	0.000213	8.51E-05	8.51E-05	0.000128	0.000128	0.000213	0.000255	0.000298	0.000213
Yoghurt	6.24E-05	6.24E-05	0	0	6.24E-05	0	6.24E-05	0	6.24E-05	6.24E-05	0	0	6.24E-05	6.24E-05	6.24E-05	6.24E-05
Starchy	0.000177	0.000265	0.000353	0.000353	0.000442	0.000442	0.00053	0.000442	0.000177	0.000265	0.000353	0.000353	0.000353	0.000353	0.000353	0.000353
Eggs	8.23E-05	8.23E-05	8.23E-05	8.23E-05	0.000123	0.000144	0.000144	0.000144	6.17E-05	6.17E-05	8.23E-05	8.23E-05	8.23E-05	0.000103	0.000103	0.000103
Transport	2.67E-05	2.76E-05	2.99E-05	3.22E-05	3.11E-05	3.18E-05	3.14E-05	2.88E-05	2.62E-05	2.62E-05	2.71E-05	2.45E-05	2.55E-05	2.54E-05	2.63E-05	2.53E-05
Total	0.007446	0.008335	0.009382	0.010613	0.010566	0.010964	0.010484	0.009227	0.007226	0.007858	0.008403	0.007548	0.008089	0.00804	0.008125	0.007675

Census data are taken from American Fact Finder at the block-group level[7]. These data provide population based on sex and age group. The age groups in the census data do not precisely align with those in NHANES, so concordance was made based on best judgement, as shown in Table S29. Census data is also adjusted for incarcerated population since their usual daily intakes are likely not well represented by NHANES. This means subtracting 1418 adults (taken from age groups based on proportion of unaltered population) from block group ‘250250801001’ as it contains the Suffolk County Correctional Facility[8].

Table S29. Concordance between NHANES and US Census age groups

NHANES age group	Census age groups
1-3	‘under 5 years’
4-8	‘5 to 9 years’
9-13	’10 to 14 years’
14-18	’15 to 17 years’, ’18 and 19 years’
19-30	’20 years’, ’21 years’, ’22-24 years’, ’25-29 years’
31-50	’30-34 years’, ’35-39 years’, ’40-44 years’, ’45-49 years’
51-70	’50-54 years’, ’55-59 years’, ’60 and 61 years’, ’62 to 64 years’, ’65 and 66 years’, ‘67 to 69 years’
71+	’70 to 74 years’, ’75 to 79 years’, ’80 to 84 years’, ‘85+ years’

With the block-group demographics data in hand and estimated environmental burdens for the different age groups and sexes, Boston’s food related environmental impacts are calculated for the 560 block-groups that comprise the city. Figures 1-2 show the estimated GWP impacts and land use for Boston’s food consumption for the year 2010.

Figure S1. 2010 food-borne GHG emissions for Boston block-groups (white indicates uninhabited block groups devoid of impacts)

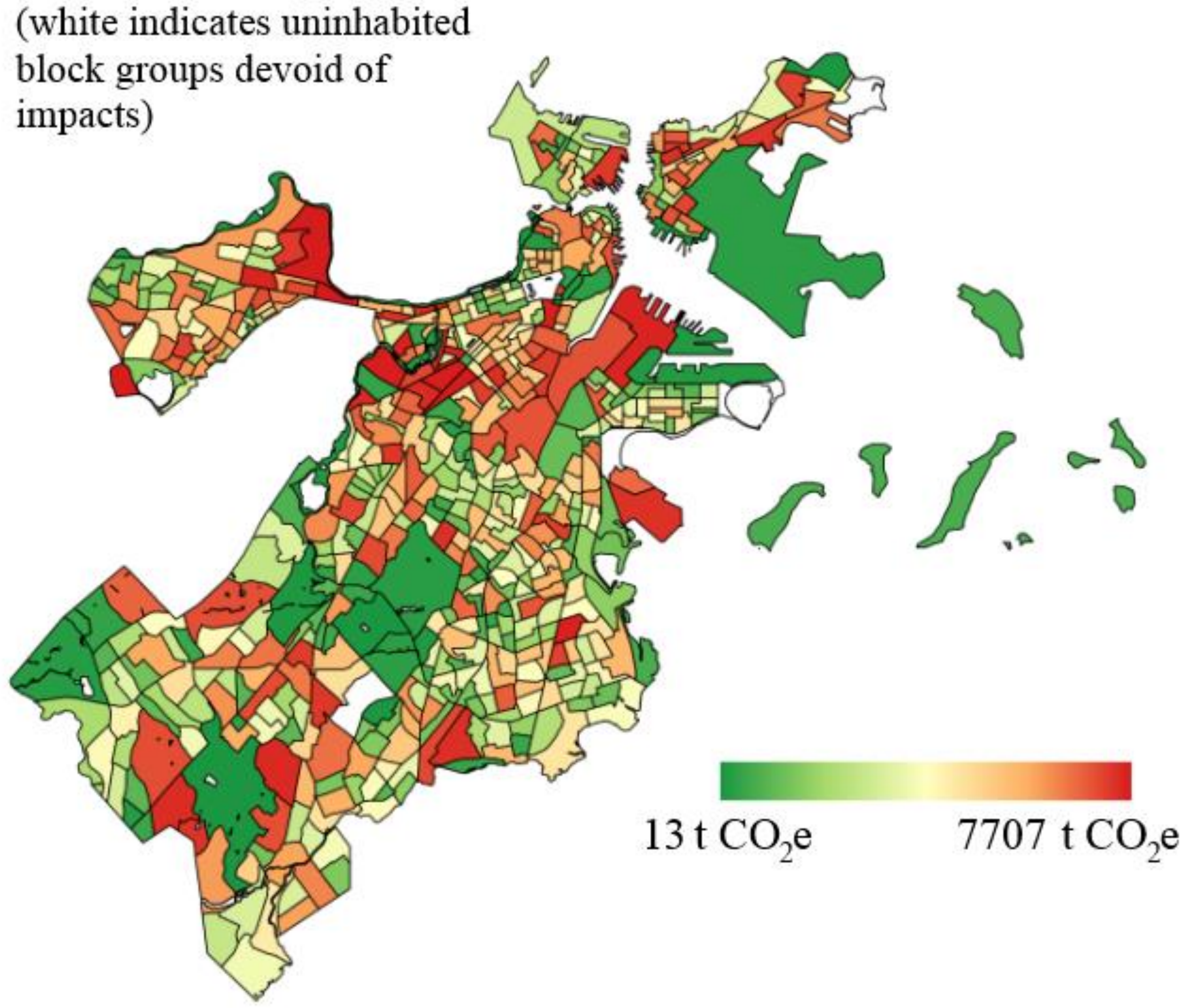
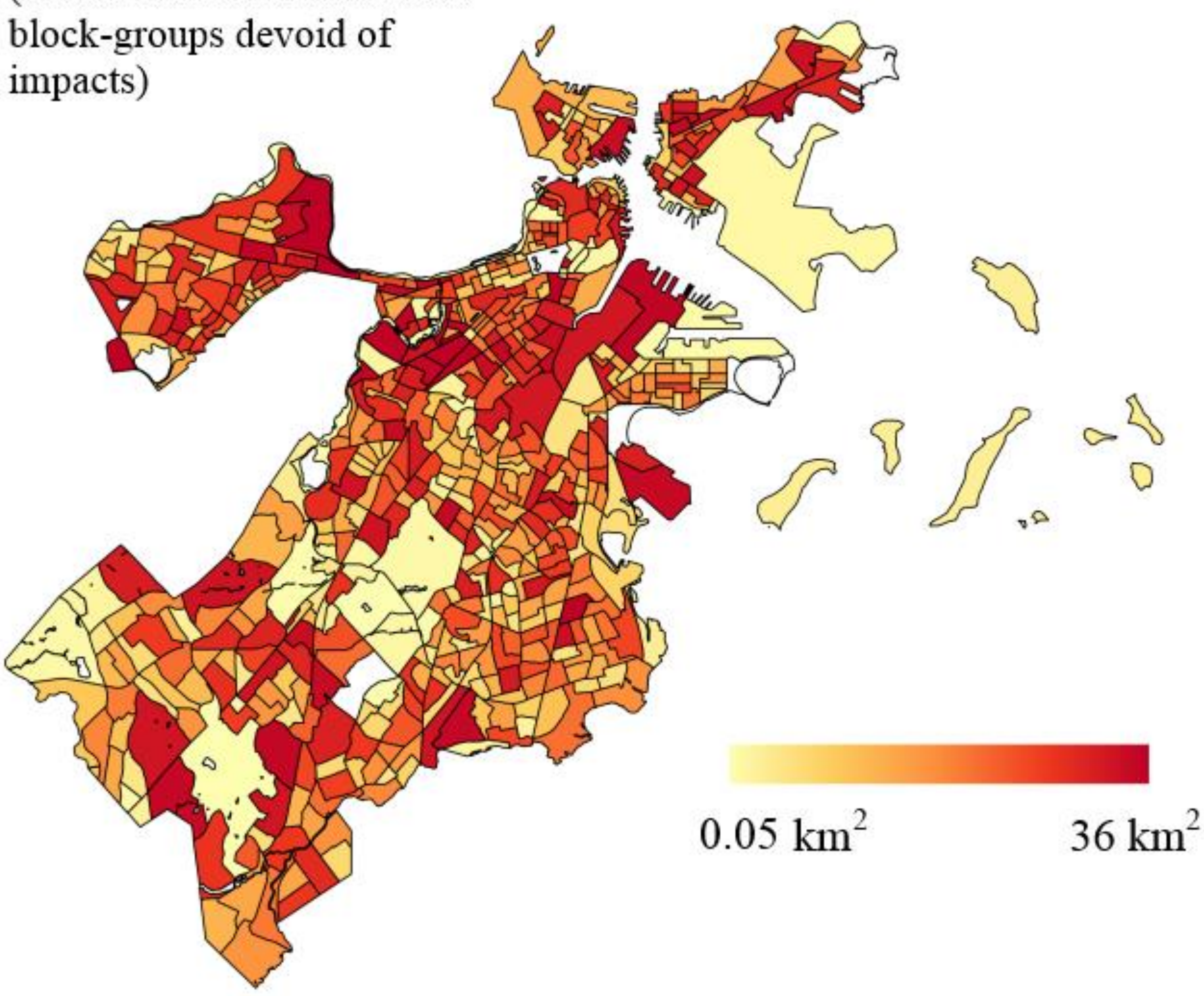


Figure S2. 2010 food-borne land use for Boston block-groups (white indicates uninhabited block-groups devoid of impacts)

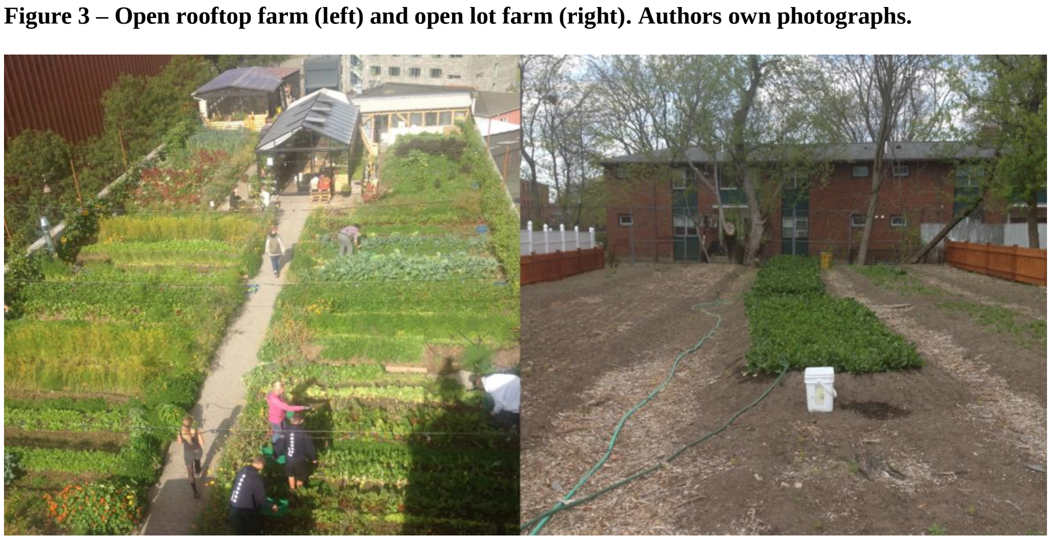


Life Cycle Inventories and LCA for Urban Agriculture

Life cycle inventories (LCI) for the urban farms build upon those from an earlier study of farms growing tomato and lettuce in Boston in New York City[9]. Of the six farms covering five UF forms from the earlier study, only three of the farms and two farm-types are used in this study, for a number of reasons:

- They produced the widest variety of crops, useful when modelling city-wide impacts of UF (difficult to model a city only consuming tomatoes)
- They represent the predominant UF forms in the study region at the time of publishing: open plots and rooftop farms (see Figure 3 for examples of each). See Goldstein et al. (2016)[10] for more information about the nuances between UF types and their divergent environmental performance.
    - Open plots typically low-tech operations, growing crops directly in local overburden or raised beds
    - Rooftop farms are identical in most respects to green roofs with the exception that they grow edible crops. Soil depth is typically equal to greater than 12”, and hence, rooftop farms qualify as intensive green roofs.
- Have superior environmental performance than conventional agriculture for some foods and by some metrics, as opposed to the other forms which had higher environmental intensities compared to conventional UF[9]. Although this skews the results in UF’s favor, it is useful in a hypothetical study of large scale urban design to quantify the potential best-case, hypothetical benefits of UF. Additionally, since UF is not universally preferable to conventional produce, this will still provide opportunities to discuss trade-offs when adapting UF.

Figure 3 – Open rooftop farm (left) and open lot farm (right). Authors own photographs.



The attributes of the utilized UF systems are outline in Table S30.

Table S30. Urban farm characteristics and crops

Location	**Farm**	**Farm Type**	**Area (m^2)**	**For profit?**	**Crops**
Boston, MA	1	open plot	560	No	tomato, bell pepper, eggplant, lettuce*
Boston, MA	2	open rooftop	1469	Yes	turnip, tomato, scallion, radish, bell pepper, lettuce, kale, cucumber, carrot, green bean
New York City	3	open plot	1269	No	turnip, tomato, squash, scallions, bell pepper, lettuce, kale, cucumber, collard greens, carrot, cabbage, beet, green bean

* Technically ‘arugula’ but assumed lettuce here since it performs the same function as lettuce (salad greens, sandwich topping, etc.)

Process-based LCA methodology is applied here. The LCA scope is production of crops and distribution to final consumers – in line with the MRIO model used to assess city-wide impacts. Where by-products occur, system expansion is applied to credit the urban farm in accordance with the ISO 14040 family[11]. The ecoinvent database version 3.2 was used to provide data on background processes and to perform the life cycle impact assessment for the different foods. Primary data was collected over the 2015 growing season. Tables S31-33 outline the Life Cycle Inventories to produce 1 kilogram of different crops from the modeled farms.

Table S31. Life Cycle Inventories per kilogram crop from farm 1

	Unit	Tomato	Bell Pepper	Eggplant	Arugula
Materials and Energy Inputs					
Capital					
Concrete, normal {US-NPCC}| production | Conseq, U	m^3	2.07E-05	3.64E-05	3.35E-05	1.25E-04
Extrusion, plastic film {US-NPCC}| production | Conseq, U	kg	1.24E-02	2.19E-02	2.02E-02	7.50E-02
Occupation, urban, continuously built	m^2	2.53E-01	4.46E-01	4.10E-01	1.52E+00
Polyethylene, high density, granulate {GLO}| market for | Conseq, U	kg	1.17E-03	2.06E-03	1.89E-03	7.04E-03
Sawnwood, hardwood, air dried, planed {RoW}| market for | Conseq, U	m^3	4.08E-05	7.19E-05	6.61E-05	2.46E-04
Steel, low-alloyed, hot rolled {US-NPCC}| market for | Conseq, U	kg	6.76E-04	1.19E-03	1.09E-03	4.08E-03
Synthetic rubber {GLO}| market for | Conseq, U	kg	8.35E-04	1.47E-03	1.35E-03	5.04E-03
Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for | Conseq, U	tkm	1.70E-01	3.00E-01	2.76E-01	1.03E+00
Wood chips, wet, measured as dry mass {RoW}| market for | Conseq, U	m^3	1.85E-01	3.26E-01	2.99E-01	1.11E+00
Operations					
Polyethylene, low density, granulate {GLO}| market for | Conseq, U	kg	3.49E-03	6.15E-03	5.66E-03	2.11E-02
Polypropylene, granulate {GLO}| market for | Conseq, U	kg	6.95E-03	1.23E-02	1.13E-02	4.19E-02
Tap water {US-Boston}| market for | Conseq, U	m^3	7.77E-02	1.31E-01	1.02E-01	1.28E-01
Transport, passenger car, large size, petrol, EURO 4 {RER}| transport, passenger car, large size, petrol, EURO 4 | Conseq, U	km	4.91E-02	8.66E-02	7.96E-02	2.96E-01
Waste					
Inert waste, for final disposal {GLO}| market for | Conseq, U	kg	1.27E-04	2.24E-04	2.06E-04	7.65E-04
Inert waste, for final disposal {US}| market for | Conseq, U	kg	1.36E-02	2.39E-02	2.20E-02	8.19E-02
PE (waste treatment) {US-NPCC}| recycling of PE | Conseq, U	kg	3.64E-03	6.41E-03	5.89E-03	2.19E-02
Rubber (waste treatment) {US-NPCC}| recycling of rubber | Conseq, U	kg	7.73E-04	1.36E-03	1.25E-03	4.66E-03
Steel and iron (waste treatment) {US-NPCC}| recycling of steel and iron | Conseq, U	kg	3.38E-04	5.96E-04	5.47E-04	2.04E-03
Waste concrete gravel {US-NPCC}| treatment of, recycling | Conseq, U	kg	4.57E-02	8.05E-02	7.40E-02	2.75E-01
Waste wood, post-consumer {GLO}| market for | Conseq, U	kg	1.30E-02	2.29E-02	2.10E-02	7.83E-02

Table S32. Life Cycle Inventories per kg crop for farm 2

	Unit	Turnip	Tomato	Scallion	Radish	Bell Pepper
Materials and Energy Inputs						
Capital						
Aluminium, primary, ingot {US}| market for | Conseq, U	kg	2.0E-06	7.8E-07	3.9E-06	1.2E-06	1.5E-06
Copper {GLO}| market for | Conseq, U	kg	6.4E-06	2.5E-06	1.3E-05	3.8E-06	4.9E-06
Crushed gravel {US-Boston} | market for | conseq, U	kg	3.2E-01	1.2E-01	6.3E-01	1.9E-01	2.4E-01
Expanded clay {US-Boston} | Market for | Conseq, U	kg	2.0E+00	7.7E-01	3.9E+00	1.2E+00	1.5E+00
Expanded shale {US-Boston} | Market for | Conseq, U	kg	1.8E-01	7.1E-02	3.6E-01	1.1E-01	1.4E-01
Extrusion, plastic film {US-MRO}| production | Conseq, U	kg	4.1E-02	1.6E-02	8.1E-02	2.4E-02	3.1E-02
Extrusion, plastic film {US-NPCC}| production | Conseq, U	kg	2.4E-02	9.3E-03	4.7E-02	1.4E-02	1.8E-02
Extrusion, plastic pipes {US-NPCC}| production | Conseq, U	kg	1.0E-03	4.1E-04	2.1E-03	6.1E-04	7.9E-04
Glass, for liquid crystal display {GLO}| production | Conseq, U	kg	1.4E-07	5.6E-08	2.8E-07	8.4E-08	1.1E-07
Nylon 6 {GLO}| market for | Conseq, U	kg	1.1E-05	4.1E-06	2.1E-05	6.2E-06	7.9E-06
Polyethylene, high density, granulate {GLO}| market for | Conseq, U	kg	3.3E-02	1.3E-02	6.5E-02	1.9E-02	2.5E-02
Polypropylene, granulate {GLO}| market for | Conseq, U	kg	1.1E-02	4.2E-03	2.1E-02	6.4E-03	8.2E-03
Steel, low-alloyed, hot rolled {US-MRO}| market for | Conseq, U	kg	1.7E-03	6.5E-04	3.3E-03	9.8E-04	1.2E-03
Steel, low-alloyed, hot rolled {US-NPCC}| market for | Conseq, U	kg	4.8E-01	1.9E-01	9.6E-01	2.9E-01	3.7E-01
Steel, low-alloyed, hot rolled {US-WECC}| market for | Conseq, U	kg	9.7E-05	3.8E-05	1.9E-04	5.7E-05	7.3E-05
Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for | Conseq, U	tkm	1.1E-01	4.3E-02	2.2E-01	6.5E-02	8.3E-02
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Conseq, U	tkm	1.9E-02	7.5E-03	3.8E-02	1.1E-02	1.4E-02
Wire drawing, copper {US-WECC}| processing | Conseq, U	kg	6.4E-06	2.5E-06	1.3E-05	3.8E-06	4.9E-06
Operations						
Phosphate fertiliser, as P2O5 {GLO}| market for | Conseq, U	kg	1.2E-03	4.7E-04	2.4E-03	7.1E-04	9.1E-04
Ammonium nitrate, as N {RER}| ammonium nitrate production | Conseq, U	kg	9.4E-04	3.7E-04	1.9E-03	5.5E-04	7.1E-04
Potassium nitrate {GLO}| market for | Conseq, U	kg	6.5E-04	2.5E-04	1.3E-03	3.8E-04	4.9E-04
Transport, passenger car, small size, petrol, EURO 5 {GLO}| market for | Conseq, U	km	1.2E+00	4.7E-01	2.4E+00	7.1E-01	9.1E-01
Electricity, low voltage, 2012-2040 average {NPCC, US only}| market for | Conseq, U	MJ	6.0E-02	2.3E-02	1.2E-01	3.5E-02	4.5E-02
Basalt {GLO}| market for | Conseq, U	kg	5.0E-02	2.0E-02	1.0E-01	3.0E-02	3.8E-02
compost {US-NPCC} | at farm | conseq, U	kg	4.3E-01	1.7E-01	8.4E-01	2.5E-01	3.2E-01
garden waste treatment {US-NPCC} | at farm | conseq, U	kg	1.3E-01	4.9E-02	2.5E-01	7.5E-02	9.5E-02
Tap water {US-Boston}| market for | Conseq, U	m^3	1.4E-02	5.6E-03	2.9E-02	8.5E-03	1.1E-02
Waste						
Aluminium (waste treatment) {US-NPCC}| recycling of aluminium | Conseq, U	kg	8.9E-07	3.5E-07	1.8E-06	5.3E-07	6.8E-07
Copper (waste treatment) {US-NPCC}| recycling of copper | Conseq, U	kg	8.9E-07	3.5E-07	1.8E-06	5.3E-07	6.8E-07
Inert waste, for final disposal {US}| market for | Conseq, U	kg	2.5E+00	9.7E-01	4.9E+00	1.5E+00	1.9E+00
PE (waste treatment) {US-NPCC}| recycling of PE | Conseq, U	kg	5.2E-02	2.0E-02	1.0E-01	3.1E-02	3.9E-02
PP (waste treatment) {US-NPCC}| recycling of PP | Conseq, U	kg	1.0E-02	4.0E-03	2.0E-02	6.0E-03	7.7E-03
Steel and iron (waste treatment) {US-NPCC}| recycling of steel and iron | Conseq, U	kg	4.7E-01	1.9E-01	9.4E-01	2.8E-01	3.6E-01

Table S32 contd. Life Cycle Inventories per kg crop from farm 2

	Unit	Lettuce	Kale	Cucumbers	Carrots	Green Bean
Materials and Energy Inputs						
Capital						
Aluminium, primary, ingot {US}| market for | Conseq, U	kg	2.6E-06	2.9E-06	9.1E-07	2.3E-06	3.3E-06
Copper {GLO}| market for | Conseq, U	kg	8.5E-06	9.4E-06	2.9E-06	7.5E-06	1.1E-05
Crushed gravel {US-Boston} | market for | conseq, U	kg	4.2E-01	4.6E-01	1.4E-01	3.7E-01	5.2E-01
Expanded clay {US-Boston} | Market for | Conseq, U	kg	2.6E+00	2.9E+00	9.0E-01	2.3E+00	3.2E+00
Expanded shale {US-Boston} | Market for | Conseq, U	kg	2.4E-01	2.6E-01	8.3E-02	2.1E-01	3.0E-01
Extrusion, plastic film {US-MRO}| production | Conseq, U	kg	5.4E-02	5.9E-02	1.9E-02	4.7E-02	6.7E-02
Extrusion, plastic film {US-NPCC}| production | Conseq, U	kg	3.1E-02	3.4E-02	1.1E-02	2.7E-02	3.9E-02
Extrusion, plastic pipes {US-NPCC}| production | Conseq, U	kg	1.4E-03	1.5E-03	4.7E-04	1.2E-03	1.7E-03
Glass, for liquid crystal display {GLO}| production | Conseq, U	kg	1.9E-07	2.1E-07	6.5E-08	1.7E-07	2.4E-07
Nylon 6 {GLO}| market for | Conseq, U	kg	1.4E-05	1.5E-05	4.8E-06	1.2E-05	1.7E-05
Polyethylene, high density, granulate {GLO}| market for | Conseq, U	kg	4.3E-02	4.8E-02	1.5E-02	3.8E-02	5.4E-02
Polypropylene, granulate {GLO}| market for | Conseq, U	kg	1.4E-02	1.6E-02	5.0E-03	1.3E-02	1.8E-02
Steel, low-alloyed, hot rolled {US-MRO}| market for | Conseq, U	kg	2.2E-03	2.4E-03	7.5E-04	1.9E-03	2.7E-03
Steel, low-alloyed, hot rolled {US-NPCC}| market for | Conseq, U	kg	6.4E-01	7.0E-01	2.2E-01	5.6E-01	8.0E-01
Steel, low-alloyed, hot rolled {US-WECC}| market for | Conseq, U	kg	1.3E-04	1.4E-04	4.4E-05	1.1E-04	1.6E-04
Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for | Conseq, U	tkm	1.5E-01	1.6E-01	5.0E-02	1.3E-01	1.8E-01
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Conseq, U	tkm	2.5E-02	2.8E-02	8.7E-03	2.2E-02	3.1E-02
Wire drawing, copper {US-WECC}| processing | Conseq, U	kg	8.5E-06	9.4E-06	2.9E-06	7.5E-06	1.1E-05
Operations						
Ammonium nitrate, as N {RER}| ammonium nitrate production | Conseq, U	kg	1.2E-03	1.4E-03	4.3E-04	1.1E-03	1.5E-03
Basalt {GLO}| market for | Conseq, U	kg	6.7E-02	7.3E-02	2.3E-02	5.9E-02	8.3E-02
compost {US-NPCC} | at farm | conseq, U	kg	5.6E-01	6.2E-01	1.9E-01	4.9E-01	7.0E-01
Electricity, low voltage, 2012-2040 average {NPCC, US only}| market for | Conseq, U	MJ	7.9E-02	8.7E-02	2.7E-02	6.9E-02	9.8E-02
garden waste treatment {US-NPCC} | at farm | conseq, U	kg	1.7E-01	1.8E-01	5.8E-02	1.5E-01	2.1E-01

Phosphate fertiliser, as P2O5 {GLO}| market for | Conseq, U	kg	1.6E-03	1.8E-03	5.5E-04	1.4E-03	2.0E-03
Potassium nitrate {GLO}| market for | Conseq, U	kg	8.6E-04	9.5E-04	3.0E-04	7.6E-04	1.1E-03
Tap water {US-Boston}| market for | Conseq, U	m^3	1.9E-02	2.1E-02	6.6E-03	1.7E-02	2.4E-02
Transport, passenger car, small size, petrol, EURO 5 {GLO}| market for | Conseq, U	km	1.6E+00	1.8E+00	5.5E-01	1.4E+00	2.0E+00
Waste						
Aluminium (waste treatment) {US-NPCC}| recycling of aluminium | Conseq, U	kg	1.2E-06	1.3E-06	4.1E-07	1.0E-06	1.5E-06
Copper (waste treatment) {US-NPCC}| recycling of copper | Conseq, U	kg	1.2E-06	1.3E-06	4.1E-07	1.0E-06	1.5E-06
Inert waste, for final disposal {US}| market for | Conseq, U	kg	3.3E+00	3.6E+00	1.1E+00	2.9E+00	4.1E+00
PE (waste treatment) {US-NPCC}| recycling of PE | Conseq, U	kg	6.9E-02	7.6E-02	2.4E-02	6.0E-02	8.5E-02
PP (waste treatment) {US-NPCC}| recycling of PP | Conseq, U	kg	1.4E-02	1.5E-02	4.7E-03	1.2E-02	1.7E-02
Steel and iron (waste treatment) {US-NPCC}| recycling of steel and iron | Conseq, U	kg	6.3E-01	6.9E-01	2.2E-01	5.5E-01	7.8E-01

Table S33. Life Cycle Inventories per kg crop from farm 3

	Unit	Turnip	Tomato	Squash	Bell Pepper	Lettuce
Material and Energy Inputs						
Capital						
Concrete, normal {US-NPCC}| production | Conseq, U	m^3	1.2E-05	9.5E-06	1.6E-05	1.6E-05	5.0E-05
Extrusion, plastic film {US-NPCC}| production | Conseq, U	kg	5.1E-03	4.1E-03	7.0E-03	7.0E-03	2.2E-02
Extrusion, plastic pipes {US-NPCC}| market for | Conseq, U	kg	5.6E-03	4.6E-03	7.8E-03	7.8E-03	2.4E-02
Polyethylene, low density, granulate {GLO}| market for | Conseq, U	kg	3.6E-03	3.0E-03	5.0E-03	5.1E-03	1.6E-02
Polypropylene, granulate {GLO}| market for | Conseq, U	kg	4.3E-03	3.5E-03	5.9E-03	6.0E-03	1.9E-02
Polyvinylchloride, bulk polymerised {GLO}| market for | Conseq, U	kg	2.7E-03	2.2E-03	3.7E-03	3.7E-03	1.1E-02
Sawnwood, hardwood, air dried, planed {RoW}| market for | Conseq, U	m^3	4.1E-05	3.4E-05	5.7E-05	5.7E-05	1.8E-04
Steel, low-alloyed {GLO}| market for | Conseq, U	kg	7.4E-04	6.1E-04	1.0E-03	1.0E-03	3.2E-03
Steel, low-alloyed, hot rolled {US-NPCC}| market for | Conseq, U	kg	2.1E-03	1.7E-03	2.9E-03	3.0E-03	9.2E-03
Straw {GLO}| market for | Conseq, U	kg	4.1E-02	3.4E-02	5.7E-02	5.7E-02	1.8E-01
Synthetic rubber {GLO}| market for | Conseq, U	kg	1.2E-04	9.7E-05	1.6E-04	1.6E-04	5.1E-04
Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for | Conseq, U	tkm	6.5E-02	5.3E-02	8.9E-02	9.0E-02	2.8E-01
Operations						
Ammonium nitrate, as N {RER}| ammonium nitrate production | Conseq, U	kg	8.2E-04	6.7E-04	1.1E-03	1.1E-03	3.5E-03
Extrusion, plastic film {US-NPCC}| production | Conseq, U	kg	7.0E-04	7.0E-04	7.0E-04	7.1E-04	6.0E-04
Occupation, urban, continuously built	m^2a	2.9E-01	2.4E-01	4.0E-01	4.0E-01	1.2E+00
Petrol, unleaded {RoW}| market for | Conseq, U	kg	7.4E-04	6.1E-04	1.0E-03	1.0E-03	3.2E-03
Phosphate fertiliser, as P2O5 {GLO}| market for | Conseq, U	kg	3.3E-04	2.7E-04	4.5E-04	4.6E-04	1.4E-03
Polyethylene, high density, granulate {GLO}| market for | Conseq, U	kg	7.0E-04	7.0E-04	7.0E-04	7.1E-04	6.0E-04
Potassium sulfate, as K2O {GLO}| market for | Conseq, U	kg	1.0E-03	8.2E-04	1.4E-03	1.4E-03	4.4E-03
Tap water {US-Boston}| market for | Conseq, U	ton	3.4E-01	1.6E-01	3.3E-01	3.3E-01	3.1E-01
Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for | Conseq, U	tkm	1.2E-02	9.6E-03	1.6E-02	1.6E-02	5.1E-02
Transport, passenger car, large size, petrol, EURO 4 {GLO}| market for transport, passenger car, large size, petol, EURO 4 | Conseq, U	km	3.7E-02	3.1E-02	5.1E-02	5.2E-02	1.6E-01
Transport, passenger car, large size, petrol, EURO 4 {RER}| transport, passenger car, large size, petrol, EURO 4 | Conseq, U	km	2.5E-02	2.5E-02	2.5E-02	2.5E-02	2.1E-02
Direct Emissions						
Carbon dioxide, fossil	kg	2.5E-03	2.1E-03	3.5E-03	3.5E-03	1.1E-02
Waste						
Inert waste, for final disposal {US}| market for | Conseq, U*	kg	-1.8E-01	-1.5E-01	-2.5E-01	-2.5E-01	-7.7E-01
PE (waste treatment) {US-NPCC}| recycling of PE | Conseq, U	kg	4.1E-03	3.5E-03	5.4E-03	5.4E-03	1.5E-02
PVC (waste treatment) {US-NPCC}| recycling of PVC | Conseq, U	kg	2.5E-03	2.1E-03	3.5E-03	3.5E-03	1.1E-02
Rubber (waste treatment) {US-NPCC}| recycling of rubber | Conseq, U	kg	5.9E-05	4.8E-05	8.2E-05	8.2E-05	2.6E-04
Steel and iron (waste treatment) {US-NPCC}| recycling of steel and iron | Conseq, U	kg	1.8E-03	1.4E-03	2.4E-03	2.5E-03	7.6E-03
Waste concrete gravel {US-NPCC}| treatment of, recycling | Conseq, U	kg	2.6E-02	2.1E-02	3.5E-02	3.6E-02	1.1E-01
Waste wood, post-consumer {GLO}| market for | Conseq, U	kg	1.9E-02	1.6E-02	2.6E-02	2.7E-02	8.3E-02

* Negative number due to avoided waste from the use of used jute bags for ground cover

Table S33 contd. Life Cycle Inventories per kg crop from farm 3

	Unit	Kale	Cucumber	Collard Greens	Carrot	Cabbage
Material and Energy Inputs						
Capital						
Concrete, normal {US-NPCC}| production | Conseq, U	m^3	8.6E-06	1.2E-05	9.8E-05	2.5E-05	8.6E-06
Extrusion, plastic film {US-NPCC}| production | Conseq, U	kg	3.7E-03	5.3E-03	4.3E-02	1.1E-02	3.8E-03
Extrusion, plastic pipes {US-NPCC}| market for | Conseq, U	kg	4.2E-03	5.9E-03	4.8E-02	1.2E-02	4.2E-03
Polyethylene, low density, granulate {GLO}| market for | Conseq, U	kg	2.7E-03	3.8E-03	3.1E-02	7.8E-03	2.7E-03
Polypropylene, granulate {GLO}| market for | Conseq, U	kg	3.2E-03	4.5E-03	3.6E-02	9.2E-03	3.2E-03
Polyvinylchloride, bulk polymerised {GLO}| market for | Conseq, U	kg	2.0E-03	2.8E-03	2.2E-02	5.7E-03	2.0E-03
Sawnwood, hardwood, air dried, planed {RoW}| market for | Conseq, U	m^3	3.1E-05	4.3E-05	3.5E-04	8.9E-05	3.1E-05
Steel, low-alloyed {GLO}| market for | Conseq, U	kg	5.5E-04	7.8E-04	6.3E-03	1.6E-03	5.5E-04
Steel, low-alloyed, hot rolled {US-NPCC}| market for | Conseq, U	kg	1.6E-03	2.2E-03	1.8E-02	4.6E-03	1.6E-03
Straw {GLO}| market for | Conseq, U	kg	3.0E-02	4.3E-02	3.5E-01	8.8E-02	3.1E-02
Synthetic rubber {GLO}| market for | Conseq, U	kg	8.8E-05	1.2E-04	1.0E-03	2.5E-04	8.8E-05
Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for | Conseq, U	tkm	4.8E-02	6.8E-02	5.5E-01	1.4E-01	4.8E-02
Operations						
Ammonium nitrate, as N {RER}| ammonium nitrate production | Conseq, U	kg	6.1E-04	8.6E-04	6.9E-03	1.8E-03	6.1E-04
Extrusion, plastic film {US-NPCC}| production | Conseq, U	kg	7.0E-04	7.2E-04	7.0E-04	7.0E-04	7.0E-04
Occupation, urban, continuously built	m^2a	2.1E-01	3.0E-01	2.4E+00	6.2E-01	2.1E-01
Petrol, unleaded {RoW}| market for | Conseq, U	kg	5.5E-04	7.8E-04	6.3E-03	1.6E-03	5.5E-04
Phosphate fertiliser, as P2O5 {GLO}| market for | Conseq, U	kg	2.4E-04	3.4E-04	2.8E-03	7.1E-04	2.4E-04
Polyethylene, high density, granulate {GLO}| market for | Conseq, U	kg	7.0E-04	7.2E-04	7.0E-04	7.0E-04	7.0E-04
Potassium sulfate, as K2O {GLO}| market for | Conseq, U	kg	7.4E-04	1.1E-03	8.5E-03	2.2E-03	7.5E-04
Tap water {US-Boston}| market for | Conseq, U	ton	5.2E-02	1.3E-01	6.0E-01	7.2E-01	5.3E-02
Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for | Conseq, U	tkm	8.7E-03	1.2E-02	9.9E-02	2.5E-02	8.7E-03
Transport, passenger car, large size, petrol, EURO 4 {GLO}| market for transport, passenger car, large size, petol, EURO 4 | Conseq, U	km	2.8E-02	3.9E-02	3.2E-01	8.0E-02	2.8E-02
Transport, passenger car, large size, petrol, EURO 4 {RER}| transport, passenger car, large size, petrol, EURO 4 | Conseq, U	km	2.5E-02	2.6E-02	2.5E-02	2.5E-02	2.5E-02
Direct Emissions						
Carbon dioxide, fossil	kg	1.9E-03	2.6E-03	2.1E-02	5.4E-03	1.9E-03
Waste						
Inert waste, for final disposal {US}| market for | Conseq, U*	kg	-1.3E-01	-1.9E-01	-1.5E+00	-3.8E-01	-1.3E-01
PE (waste treatment) {US-NPCC}| recycling of PE | Conseq, U	kg	3.2E-03	4.3E-03	3.0E-02	8.0E-03	3.2E-03
PVC (waste treatment) {US-NPCC}| recycling of PVC | Conseq, U	kg	1.9E-03	2.6E-03	2.1E-02	5.4E-03	1.9E-03
Rubber (waste treatment) {US-NPCC}| recycling of rubber | Conseq, U	kg	4.4E-05	6.2E-05	5.0E-04	1.3E-04	4.4E-05
Steel and iron (waste treatment) {US-NPCC}| recycling of steel and iron | Conseq, U	kg	1.3E-03	1.8E-03	1.5E-02	3.8E-03	1.3E-03
Waste concrete gravel {US-NPCC}| treatment of, recycling | Conseq, U	kg	1.9E-02	2.7E-02	2.2E-01	5.5E-02	1.9E-02
Waste wood, post-consumer {GLO}| market for | Conseq, U	kg	1.4E-02	2.0E-02	1.6E-01	4.1E-02	1.4E-02

* Negative number due to avoided waste from the use of used jute bags for ground cover

Table S33 contd. Life cycle inventories per kg crop from farm 3

	Unit	Beet	Green Bean	Scallion
Capital				
Concrete, normal {US-NPCC}| production | Conseq, U	m^3	1.8E-05	9.5E-06	5.3E-05
Extrusion, plastic film {US-NPCC}| production | Conseq, U	kg	7.8E-03	4.1E-03	2.3E-02
Extrusion, plastic pipes {US-NPCC}| market for | Conseq, U	kg	8.7E-03	4.6E-03	2.6E-02
Polyethylene, low density, granulate {GLO}| market for | Conseq, U	kg	5.6E-03	3.0E-03	1.7E-02
Polypropylene, granulate {GLO}| market for | Conseq, U	kg	6.6E-03	3.5E-03	2.0E-02
Polyvinylchloride, bulk polymerised {GLO}| market for | Conseq, U	kg	4.1E-03	2.2E-03	1.2E-02
Sawnwood, hardwood, air dried, planed {RoW}| market for | Conseq, U	m^3	6.4E-05	3.4E-05	1.9E-04

Steel, low-alloyed {GLO}| market for | Conseq, U	kg	1.1E-03	6.1E-04	3.4E-03
Steel, low-alloyed, hot rolled {US-NPCC}| market for | Conseq, U	kg	3.3E-03	1.7E-03	9.8E-03
Straw {GLO}| market for | Conseq, U	kg	6.4E-02	3.4E-02	1.9E-01
Synthetic rubber {GLO}| market for | Conseq, U	kg	1.8E-04	9.7E-05	5.4E-04
Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for | Conseq, U	tkm	1.0E-01	5.3E-02	3.0E-01
Operations				
Ammonium nitrate, as N {RER}| ammonium nitrate production | Conseq, U	kg	1.3E-03	6.7E-04	3.8E-03
Extrusion, plastic film {US-NPCC}| production | Conseq, U	kg	7.0E-04	7.0E-04	6.8E-04
Occupation, urban, continuously built	m^2a	4.5E-01	2.4E-01	1.3E+00
Petrol, unleaded {RoW}| market for | Conseq, U	kg	1.2E-03	6.1E-04	3.4E-03
Phosphate fertiliser, as P2O5 {GLO}| market for | Conseq, U	kg	5.1E-04	2.7E-04	1.5E-03
Polyethylene, high density, granulate {GLO}| market for | Conseq, U	kg	7.0E-04	7.0E-04	6.8E-04
Potassium sulfate, as K2O {GLO}| market for | Conseq, U	kg	1.6E-03	8.2E-04	4.6E-03
Tap water {US-Boston}| market for | Conseq, U	ton	5.2E-01	2.7E-02	4.5E-02
Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for | Conseq, U	tkm	1.8E-02	9.6E-03	5.4E-02
Transport, passenger car, large size, petrol, EURO 4 {GLO}| market for transport, passenger car, large size, petol, EURO 4 | Conseq, U	km	5.8E-02	3.1E-02	1.7E-01
Transport, passenger car, large size, petrol, EURO 4 {RER}| transport, passenger car, large size, petrol, EURO 4 | Conseq, U	km	2.5E-02	2.5E-02	2.4E-02
Direct Emissions				
Carbon dioxide, fossil	kg	3.9E-03	2.1E-03	1.2E-02
Waste				
Inert waste, for final disposal {US}| market for | Conseq, U*	kg	-2.8E-01	-1.5E-01	-8.2E-01
PE (waste treatment) {US-NPCC}| recycling of PE | Conseq, U	kg	6.0E-03	3.5E-03	1.6E-02
PVC (waste treatment) {US-NPCC}| recycling of PVC | Conseq, U	kg	3.9E-03	2.1E-03	1.2E-02
Rubber (waste treatment) {US-NPCC}| recycling of rubber | Conseq, U	kg	9.2E-05	4.8E-05	2.7E-04
Steel and iron (waste treatment) {US-NPCC}| recycling of steel and iron | Conseq, U	kg	2.7E-03	1.4E-03	8.1E-03
Waste concrete gravel {US-NPCC}| treatment of, recycling | Conseq, U	kg	4.0E-02	2.1E-02	1.2E-01
Waste wood, post-consumer {GLO}| market for | Conseq, U	kg	3.0E-02	1.6E-02	8.8E-02

* Negative number due to avoided waste from the use of used jute bags for ground cover

Two metrics are assessed in this LCA: GWP and land use. GWP is assessed using the IPCC 2013 methodology over a 100 year time horizon[12]. Land use is assessed using the ReCiPe LCIA methodology[13], which is an un-weighted method for accounting land use (it is time weighted in that it measure area × time, but since the time component is equal to a single year for all UF operations here and the MRIO model, the time weighting is inconsequential here). ReCiPe does differentiate between urban and agricultural land occupation. Here we sum both land uses to account for total land use by UF, both indirect and direct. Table S34 outlines the impacts for each product from the UF operations for both GWP and land use.

Table S34. GWP and land use for different UF crops

Crop	Farm	GWP (kg CO^2e/kg crop)	Land use (m^2/kg)
Beet	3	0.399	0.713
Bell Pepper	1	0.156	1.542
Bell Pepper	2	1.165	0.245
Bell Pepper	3	0.304	0.638
Cabbage	3	0.116	0.342
Carrot	2	1.793	0.377
Carrot	3	0.549	0.989
Collard Greens	3	1.218	3.851
Cucumber	2	0.706	0.149
Cucumber	3	0.181	0.479
Eggplant	1	0.127	1.417
Green Beans	2	2.547	0.536
Green Beans	3	0.114	0.374
Kale	2	2.256	0.475
Kale	3	0.153	0.518
Lettuce	1	0.263	5.244
Lettuce	2	2.088	0.437
Lettuce	3	0.448	1.798
Radish	2	0.915	0.193
Scallion	2	3.062	0.644
Scallion	3	0.551	2.092
Squash	3	0.302	0.633
Tomato	1	0.104	0.880
Tomato	2	0.625	0.129
Tomato	3	0.134	0.344
Turnip	2	1.547	0.326
Turnip	3	0.261	0.462

Comparative performance of UF and conventional agriculture

GWP for the conventional food are taken from Heller and Keoleian's work on the GWP impacts of the US diet[14]. Their work includes a review of LCAs of different food products, including the range of reported findings and average across studies. Here we use their reported averages as a proxy for conventional agriculture. As their numbers are only for production, we add on transport impacts in accordance with Pirog and Benjamin's work on 'food miles' for conventional food products heading to Iowa (data for the US northeast remain in absentia)[15]. Transport impacts are taken as $9.7*10^{-5}$ kg CO_2e/kgkm (ecoinvent 3.2 process 'Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Conseq, U'). Land use is taken as direct land occupation: calculated as the total 3 year average (2012-2014) annual US production divided by the total US cultivated area from the USDA annual vegetable statistics (beet, eggplant, kale, collards, turnip, scallion taken from 2002 survey)[16,17]. Direct land use is taken here as this is far and away the largest driver of this indicator for vegetal foods and should cover nearly 100% of land use. Values are corrected for food losses from the USDA LAFA statistics[2]. Table S35 outlines the impacts of the conventional goods for both GWP and land use.

Table S35. GWP and land use for conventional produce

Product	Transport (km)	Losses (%)	GWP – production (kg CO_2e/kg)	GWP – transport (kg CO_2e/kg)	GWP – total (kg CO_2e/kg)	Land Use (m^2/kg)
Beet	1759	6.5	0.33	0.28	0.65	0.40
Bell Pepper	1589	7.8	0.88	0.25	1.23	0.29
Cabbage	719	6.5	0.12	0.11	0.25	0.27
Carrot	1838	5.1	0.53	0.29	0.86	0.28
Collard Greens	1815	37.5	0.33	0.29	0.99	1.10
Cucumber	1277	6.1	0.66	0.20	0.92	0.48
Eggplant	1277	21.3	1.30	0.20	1.91	0.43
Green Beans	1313	18.4	0.73	0.21	1.15	1.93
Kale	1815	39.2	0.33	0.29	1.01	0.75
Lettuce	1823	7.7	1.08	0.29	1.48	0.27
Radish	1759	21	0.33	0.28	0.77	1.25
Scallion	1759	9.8	0.33	0.28	0.67	0.18
Squash	1277	12.5	0.09	0.20	0.33	0.64
Tomato	1569	5.2	0.67	0.25	0.97	0.34
Turnip	1815	6.5	0.33	0.29	0.66	0.80

Combining primary data on yields from the UF operations, we calculate the marginal change in environmental performance of Boston per meter UF cultivating vegetable x, $\frac{dI_x}{dA}$, as:

$$(4) \qquad \frac{dI_x}{dA} = \frac{dm_i}{dA}\left(i_{x,UA} - i_{x,conv}\right)$$

Where $\frac{dm_i}{dA}$ is the change in mass of vegetable per unit area in kilograms (annual yield), $i_{x,UA}$, the environmental impact from producing one kilogram of vegetable x with UF, and $i_{x,conv}$ the environmental impact of producing one kilogram of vegetable x with conventional agriculture (crediting for the substituted conventional crop). Table S36 outlines the predicted change in Boston's food-borne environmental impacts by implementing UF. It should be noted that the yield for UF includes 'dead space' on the farm where cultivation is not occurring (e.g. sheds, footpaths, etc.) and not just productive area. Where farms 1 and 3 produce the same product, the average yield and environmental burdens have been used.

Table S36. UF yields and marginal shifts in GWP and land use per m2 UF implemented in Boston

Crop	Farm(s)	Yield (kg/m^2)	Marginal GWP Shift (kg CO_2e/m^2 UF)	Marginal Land Use Shift (m^2/m^2 UF)
Beet	3	2.26	-0.57	0.70
Bell Pepper	1 and 3	2.30	-2.29	1.84
Bell Pepper	2	2.44	-0.15	-0.65
Cabbage	3	4.70	0.43	0.36
Carrot	2	1.59	1.47	0.16
Carrot	3	1.63	-0.51	1.16
Collard Greens	3	0.41	0.10	1.14
Cucumber	2	5.28	-1.11	-1.73
Cucumber	3	3.34	-2.46	-0.01
Eggplant	1	2.27	-4.04	2.24
Green Beans	3	4.27	-3.06	-4.36
Green Beans	2	1.12	1.57	-1.56
Kale	2	1.26	1.57	-0.35
Kale	3	4.72	-4.24	-1.96
Lettuce	1 and 3	0.80	-0.90	2.61
Lettuce	2	0.80	0.49	0.14
Radish	2	3.11	0.45	-3.29
Scallion	2	0.93	2.22	0.43
Scallion	3	0.76	-0.25	1.42
Squash	3	2.54	-0.08	-0.01
Tomato	1 and 3	2.94	-2.50	0.80
Tomato	2	4.70	-1.61	-0.99
Turnip	2	1.84	1.63	-0.86
Turnip	3	3.50	-1.39	-1.17

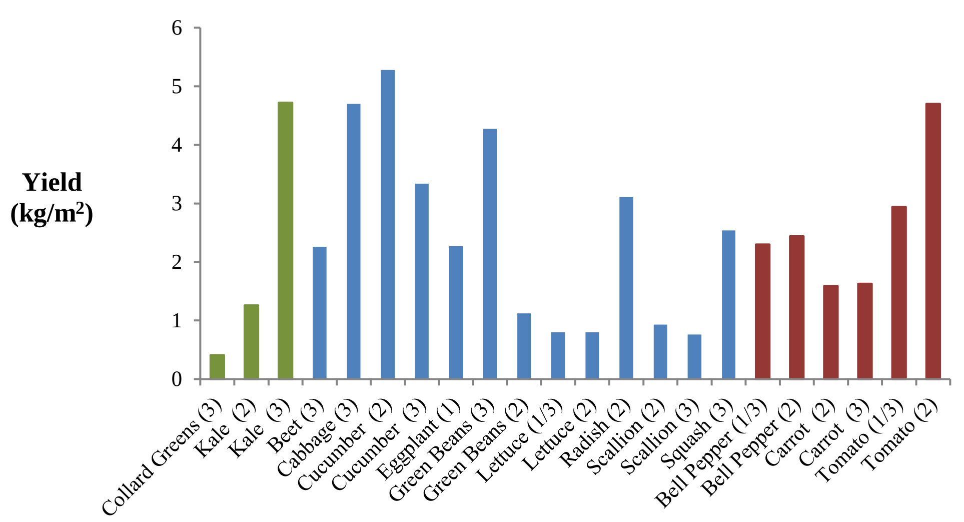


Figure 4. Yield for dark green (green), other (blue) and red and orange (red) vegetables. Farm(s) listed in brackets.

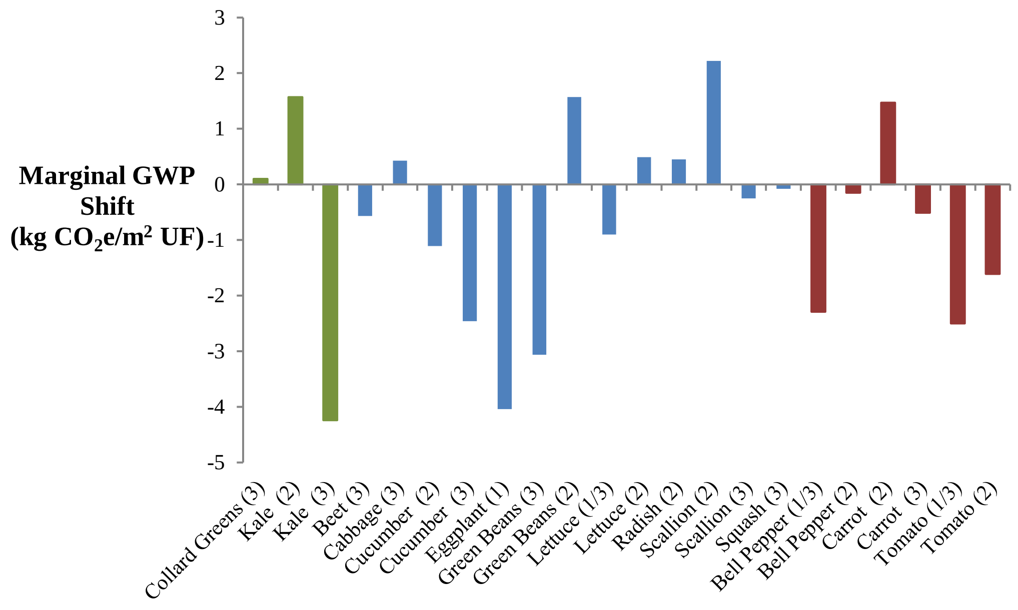


Figure 5. Marginal GWP shift per square meter UF grown for dark green (green), other (blue) and red and orange (red) vegetables. Farm(s) listed in bracets.

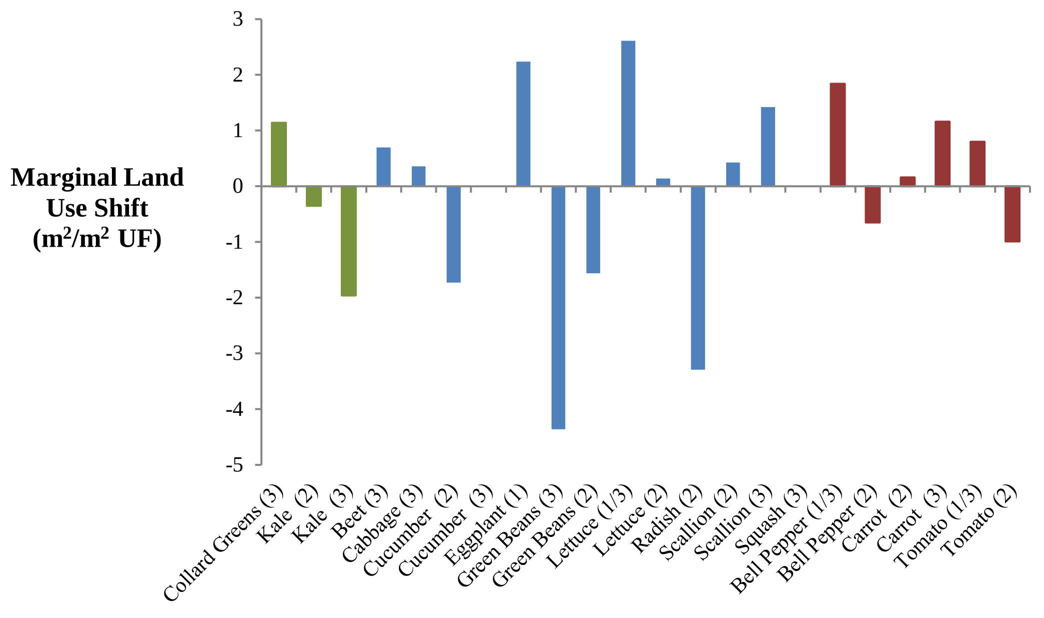


Figure 6. Marginal land use shift per square meter UF grown for dark green (green), other (blue) and red and orange (red) vegetables. Farm(s) listed in bracets.

UF Space Availability

Space for UF in Boston was estimated for ground and roof. Potential ground space was estimated by two methods: subtractive and additive. Roof space is performed in an additive manner. In this assessment, soil contamination is not considered when assessing the suitability of a piece of land for UF. Soil contamination is a major issue in US cities, particularly older cities with industrial heritage[18]. Moreover, shading effects from buildings are also ignored. As such, these estimates should be viewed as upper bounds for UF available space in Boston for both ground methods.

Ground Space – Additive

The additive approach for UF space starts with the assumption that the area of UF space in Boston is 0 m^2. Then utilizing a variety of data sources, we look at individual pieces of land, assesse their suitability for UF and add them to amount of space suitable for UF. The data sources are the 2016 Tax Assessment Parcel and open space maps, sourced from the City of Boston's Open Data Initiative[19] and the Massachusetts land use map from their geographic information system (GIS) data repository[20].

Tax assessment parcels data for the year 2016 includes all tax assessment parcels in Boston (166,248) including their land use according to the Massachusetts property classification system under the 'PTYPE' field in the raw data. Table S37 outlines the land uses we consider suitable for UF as they are not currently occupied by buildings or other productive land uses.

Table S37. UF suitable property types from tax assessment data

Land Use Code ('PTYPE')	Description
130	Residential land
131	Residential land (secondary)
132	Residential land (unusable)
390	Commercial land
391	Commercial land (secondary)
392	Commercial land (unusable)
440	Industrial land
441	Industrial land (secondary)
442	Industrial land (unusable)
337	Parking lot
359	Condo parking (commercial)
387	Pay parking lot
108	Condo parking (residential)
119	Residential parking lot

Parking lots have been included here to test the impact of their inclusion on the results, since they could be considered transitional land uses. Moreover, some of the parking lots are subterranean, making them unsuitable for the UF forms considered here, though this is not indicated by the parcel assessment data. Results include assessments with and without parking included to gauge the sensitivity of the results to their inclusion.

Community garden data includes the locations of existing UF in the city as designated by the Open Space map in the city's data repository. We assume that all operating community gardens are valid for this assessment.

Lastly, the state land use map from 2005 is used to include the land uses outlined in table S38 as described by the field 'LUCODE' in the data.

Table S38. UF suitable land uses from state land use map

Land Use Code ('LUCODE')	Description
1	Cropland
2	Pasture
6	Open Land
17	Transitional
36	Nursery
40	Brushland/Successional

Data are imported into the GIS software QGIS 2.4.0 and corrected for two issues:

- Residential and condo parking lots are checked for double counting, since the same assessment parcel are listed multiple times if the different parking spots on the same piece of area are owned by different individuals
- Where UF suitable plots intersected, the overlapping portion is subtracted from one of the layers. See figure 7.
- Plots with average slopes greater than 10°, as determined from digital elevation models provided by the National Oceanic and Atmospheric Administration (NOAA)[21], were deemed too steep for agriculture and excluded.

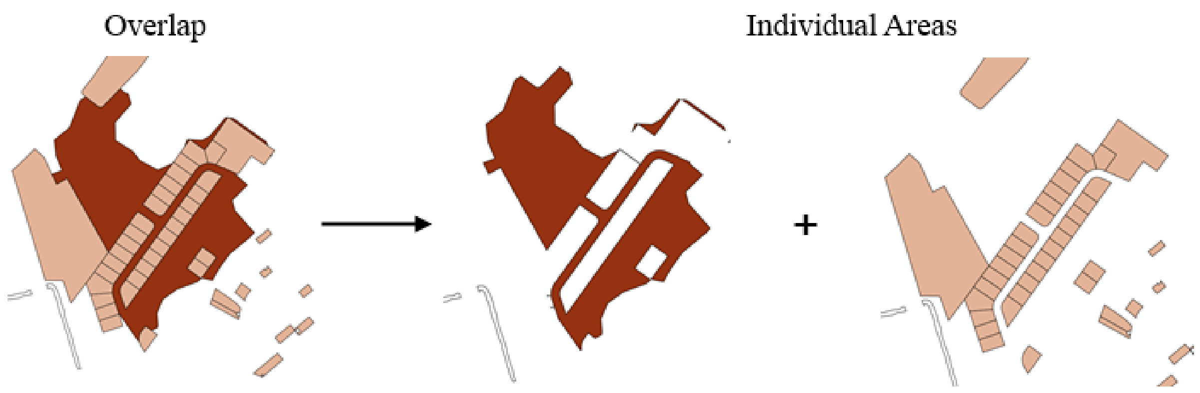


Figure 7. The disaggregation of overlapping areas in QGIS.

With a unique set of non-intersecting UF suitable plots, the area of each plot is calculated in QGIS and added to estimate total UF available space for Boston. Results are listed in table S39. QGIS also allows one to determine if an UF suitable plot lies within a block-group, providing area totals for each block-group (not shown here, but shown in Figures 2 a-b of the article).

Table S39. UF space using additive method

Land Use	**Number of UF Suitable Sites**	**Average Site Size (standard deviation) m^2**	**Total UF Space (m^2)**	**Total UF Space (acres)**
Vacant residential*	5865	412 (1637)	2421080	599
Vacant commercial*	1267	1026 (3826)	1300847	322
Vacant industrial*	162	1375 (3668)	222860	55
Existing community gardens	123	1122 (2235)	138063	34
Pasture	1	13184 (0)	13184	3
Transitional	34	10271 (13569)	349228	86
Nursery	15	10127 (11699)	151906	38
Cropland	14	6395 (7739)	89525	22
Brushland/Successional	17	24979 (53946)	421542	104
Open Land	159	13825 (29049)	2198200	544
Residential Parking*	262	805 (4080)	210850	52
Commercial Parking*	630	892 (2698)	562124	139
Boston Total	8549	944 (5740)	8079409	2000

* Sum of their respective sub-uses

Ground Space – Subtractive

Contrasting with the additive method, here we start with the assumption that 100% of Boston is suitable for UF and then subtract those areas deemed unsuitable for farming. As with the additive approach, overlapping areas are removed to avoid double counting. Table S40 lists the land types considered unsuitable for ground-based US, their areas and the total UF available land in Boston using the subtractive estimation method.

Table S40. Boston UF ground space using subtractive method

Land Type	**Data Source**	**Total Area (m2)**	**Total Area (acres)**
Steep areas	NOAA[21]	480475	119
Parks and sports fields	MassGIS ('OpenSpace' dataset)[22]	2818969	698
Protected open space	MassGIS ('OpenSpace' dataset)[22]	19461607	4817
Temporarily protected open space	MassGIS ('OpenSpace' dataset)[22]	11443	3
Cemeteries	MassGIS ('OpenSpace' dataset)[22]	3186303	789
Buildings	Boston Open Data('Buildings' dataset)[19]	21946457	5433
Impervious surfaces (roads, sidewalks, etc.) – buildings removed	Boston Open Data('Impervious Surfaces' dataset)[19]	35926938	8893
Airport	Boston Open Data[19]	6172008	1528
Total	-	90004200	22278
Total Boston Area			
Boston Total Area	Boston Open Data ('Boundary' dataset)[19]	125095606	30964
Total UF Area			
Total UF Area	-	35736010	8846

As with the additive scenario, QGIS is used to allocate available space to the block-groups in Boston.

Rooftop Space

The first step in estimating the amount of rooftop area available for UF in Boston is to get a clean data set of pertinent information of the Boston building stock. Davila and colleagues already outlined the process in detail[23], but in a nutshell it involves combining three datasets: the Boston property tax assessment for the year 2014[24], the 2016 tax parcel assessment data[19] and the geospatial building data for Boston[19].

The property tax assessment is required as it is the most up to date and detailed assessment of building attributes for the city and contains all buildings and sub-units within buildings. Because of the latter point, it contains double counting of buildings that contain multiple apartment units. Double counted units were removed using a Python 2.7 script which identifies buildings with multiple units based on the 'CM_ID' field. While consolidating multiple units to a single entry, we also assign the heating and cooling type of the building based on the majority heat and cooling types for the units within the building. This initial data parsing reduces the tax records from 164,092 entries to 100,858 entries.

Although the tax records data contains the most detailed information, they contain no spatial data and cannot be mapped nor attributed to block-groups. To overcome this we link the 10 digit property ID key 'Parcel_ID' in the tax record with the synonymous 'PID_LONG' key in the spatially explicit tax assessment data. Minor mismatches between the datasets shave the number of entries down to 98,865. Table S41 outlines the various fields utilized in this process and their purposes.

Table S41. Fields used in joining tax data sets

Field	**Dataset**	**Purpose**
CM_ID	2014 Tax records	Identify duplicate building entries
U_Heat	2014 Tax records	Identify the predominant heating type in multi-unit dwellings
U_AC	2014 Tax records	Identify if a majority of units have air conditioning in multi-unit dwellings
Parcel_ID	2014 Tax records	Join data tax record data with tax parcel assessment polygons
PID_Long	Tax parcel assessment data	Join tax parcel assessment polygons with 2014 tax record data

Although this dataset is spatially explicit, it still contains numerous errors in terms of non-existent buildings, improper building footprints and building types that are not suitable for UF applications. Moreover, the tax data does not contain reliable estimates of building heights. To overcome this we join the generated parcel data set with the building data set, since the latter contains information on building types and can be used to more accurately calculate building footprints. The spatially explicit data is then mapped as polygons in QGIS, converted to centroids and spatially joined to building polygon data. Figure 5 illustrates this process in QGIS.

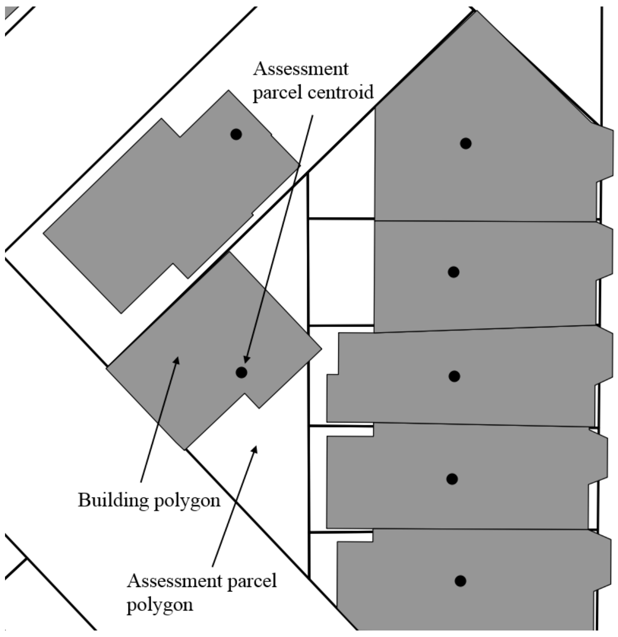


Figure 8. Joining the tax data with the building polygons

Building data is also spatially joined with data on historic preservation districts from the Boston Open Data Initiative[19], as buildings in these districts are not permitted to make changes to their exterior appearance, and should be excluded from UF use. The four joined datasets contain the necessary information for estimating UF building space in Boston, outlined in table S42.

Table S42. Properties used for calculating UF suitability

Building Property	Key	Dataset
Year of construction	'YR_BUILT'	2014 Tax assessment data
Number of floors	'NUM_FLOORS'	2014 Tax assessment data
Roof type	'R_ROOF_TYP'	2014 Tax assessment data
Heating type	'R_HEAT_TYP'	2014 Tax assessment data
Presence of air conditioning	'R_AC'	2014 Tax assessment data
Ground elevation	'GROUND_ELE'	Building data
Roof elevation	'ROOF_ELE'	Building data
Building Type	'IEL_TYPE'	Building data
Building Area	Calculated in QGIS	Building data
Presence in historic preservation district	Generated in QGIS with spatial join	Historic Districts

The final step in cleaning the building data is to remove buildings lacking information on year built, height (either no data on number of floors or incomplete elevation data) and unsuitable for UF. The latter is done using the 'IEL_TYPE' key of the building data by excluding ruins, foundations, etc. After all of the manipulations, the cleaned dataset of collated building and tax data contains 76,170 buildings (69,857 when historical buildings are excluded).

Actually determining the area of Boston's buildings available for UF is impossible since we lack structural analyses of the buildings that would allow us to determining their individual capacities for supporting the load of a rooftop farm. However, we can use three indicators to estimate UF rooftop space: building age, building height and roof type.

Building age is justified in the sense that the introduction of building codes and standards has led to the gradual infiltration of more structurally sound buildings through mandated snow loading capacity, etc. Thus, here we assume that older buildings are less likely to be suited for UF than new ones. This is a gross simplification, since old buildings, particularly older factories and cast iron buildings are designed to support significantly heavier loads than they are burdened with not in their post-industrial uses. As such, we run multiple scenarios building age is used as a cutoff for UF consideration. The cutoff construction years range from 1900 to 2000 in ten year intervals. This covers around ¾ of Boston's building stock by both number of buildings and area. Figure 6 is a histogram showing the effects of different construction year cutoffs on the number and area of buildings considered.

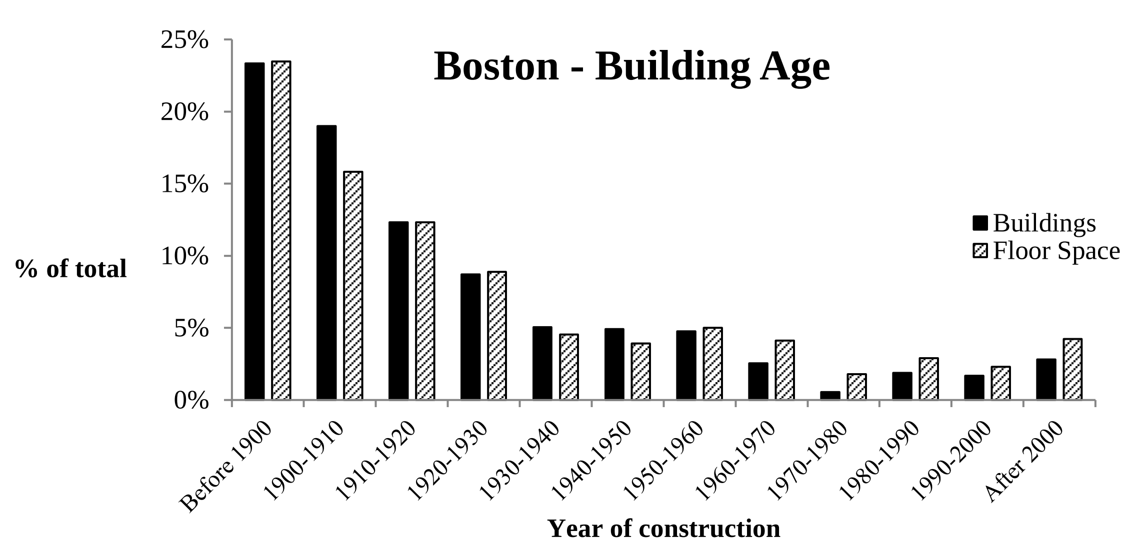


Figure 9. Histogram of building numbers and area within different intervals of construction years.

Height is also a natural limiting factor on UF suitability, since stronger winds above certain heights not only pose a challenge to the stability of the growing medium, but also a safety issue to farm workers. Heights are taken as the difference of ground and roof elevations in the building data, and where these are lacking, the number of floors times the average floor height of 3.42 m as determined from those buildings within the building data set that contain both number of floors and elevation data. Looking at the histogram of number of buildings and building area with within different height ranges in Figure 7, it can be seen that only small fraction of Boston's building stock is over 30 m tall, and hence this is taken as the maximum allowable height for a building to be considered UF appropriate.

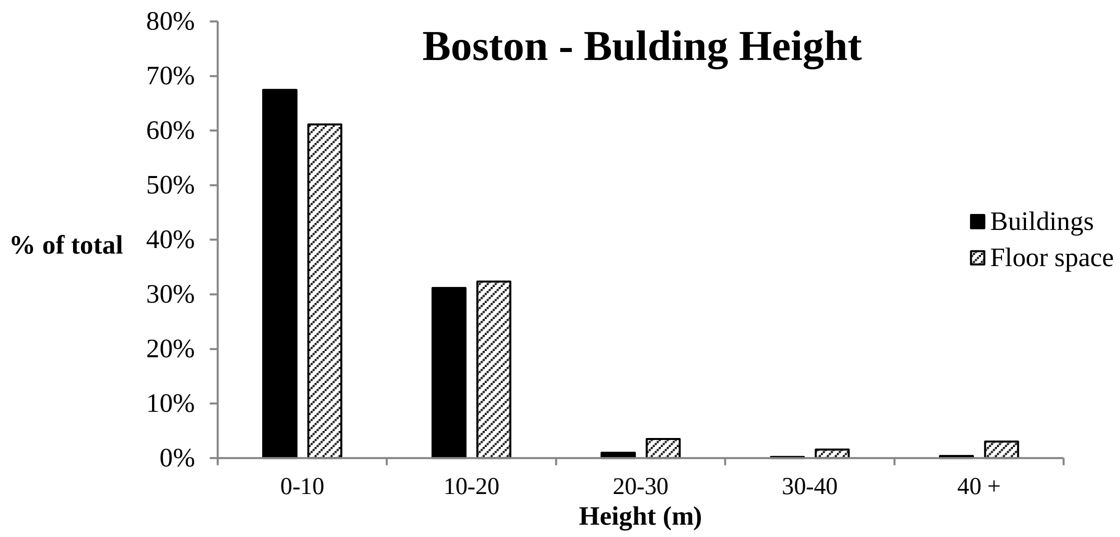


Figure 10. Number of buildings and building area in Boston for different building height ranges

Lastly, roof type is a natural indicator of UF suitability, since rooftop farms necessitate flat roofs. Only some of the tax data entries specify the roof type. Where no data on roof type was given, the roof type was assigned to a building probabilistically based on the representation of flat roofs in the general New England building stock. For commercial buildings this is a 25.2% probability according to the commercial building energy consumption survey[25]. As this data is lacking in the analogous residential survey, it is estimated as the percentage of buildings in our generated building data set with flat roofs, 21.3% (11735 of 55026 entries with roof data).

Table S43 shows the results of the different cutoff years, the height limit and the probabilistic assignment of roof top averaged over 100 runs.

Table S43. Estimates of rooftop suitable UF based on different cutoff years, a height limit of 30 m and the presence of a flat roof dictated by probabilistically over 100 Monte Carlo simulations

Cutoff Year	Building Space (m^2)	SD (m^2)	Building Space (acres)	SD (acres)
1900	1714149	34113	424	8
1910	942317	35025	233	9
1920	672546	32088	166	8
1930	512520	31076	127	8
1940	440620	29107	109	7
1950	406841	30041	101	7
1960	334557	24713	83	6
1970	253619	19861	63	5
1980	215278	19309	53	5
1990	156922	15967	39	4
2000	104950	12094	26	3

Urban metabolism interactions

This study accounts for three direct material/energy exchanges between farm and city: runoff retention, solid waste assimilation and building energy reductions.

Runoff retention

The engineering of the modern city has seen the channelizing, rerouting and burying of urban streams. The proliferation of impermeable surfaces throughout cities that prevent the penetration of the rainwater into the soil mean that much of this water is directed towards stormwater sewers, eventually bound for wastewater treatment instead of recharging groundwater aquifers or surface waters. The net effect is that when it rains, large volumes of water are unnecessarily sent for treatment or during intermittent heavy rain events, sewer capacity is exceeded and water from sewage pipes is vented to local surface waters[26]. If the stormwater is combined with sanitary water in a combined sewer, then heavy rain events can lead to the release of raw sewage when the sewers overflow in combined-sewer-overflow events (CSO)[27]. Boston has over 235 miles of combined-sewers and 37 CSO outfalls and is negatively impacted by CSO events during particularly intense or long rainfalls[27]. Since UF occasionally replaces impermeable area with soil that can either retain water for crop uptake or provide a hydraulic conduit between surface and groundwater it is important to model how the potential runoff mitigation provided by UF in Boston.

Here we consider to situations where UF implementation in Boston obviates runoff to the sewers: where UF replaces ground parking and where it is placed on buildings. We provide upper and lower bounds of runoff retention based on field studies of extensive green roofs. Lower and upper retention rates are taken as 50%[28] and 74% [29], respectively. The same rates are applied to ground UF since they are also representative of runoff retention on permeable land[26]. This method ignores the heterogeneity of soil characteristics and resultant runoff retention, but as a basic estimate to gauge the impact of UF on Boston's hydrology it should suffice to identify whether the scale of these impacts are significant or miniscule. Moreover, this method ignores the ability for UF to reduce the prevalence of CSOs and toxic fallout from sewage releases. However, quantifying such impacts would require detailed information on CSO outfall locations and local pollution assimilation capacity that is beyond the scope of this exercise.

In assessing the GWP and land use impacts from avoided stormwater treatment, we use the ecoinvent 3.2 process 'Wastewater, unpolluted {RoW}| treatment of, capacity 5E9l/year | Conseq, U' to model wastewater treatment in Boston. Using the aforementioned GWP and land use methods we calculate 0.293 kg CO_2e and 0.0260 m^2 in avoided impacts per m^3 avoided wastewater treatment.

Precipitation is taken as the 2000-2015 annual Boston average of 1.11 m[30].

Solid waste assimilation

We use primary data collected from the urban farms we have the following compost application rates:

- Roof based UF: 2.8 kg compost/m^2
- Ground based UF: 0.3 kg compost/m^2

Though the lower compost usage for roof based UF seems counterintuitive, it is a result of wind-related soil losses from green roofs and the need to supplement the expanded shale/concrete grow media with medium rich in nutrients and organic carbon. Ground-based UF is less affected by soil loss and tends to occur in a top-soil matrix rich in organic carbon and with greater nutrient sorption capacity, and hence, does not demand the same volume of nutrient/organic additions as the rooftop farms.

To convert from deposited compost to mass of avoided waste, we assume a mass loss of 32% from waste compost. This is a conservative estimate based on the open windrow composting of garden waste in the US[31]. Applying this factor we find that rooftop farms and ground-based UF can assimilate 4.1 and 0.4 kg organic waste/m^2, respectively. In modelling the environmental impacts of waste assimilation, we allocate the waste treatment and related avoided fertilizer production to the previous life-cycle of the waste, and the delivery of the waste to the UF site to the farms.

Building Energy

In modelling the potential interactions between a building's energy system and farm the following assumptions are made:

- No direct coupling of the building energy system and urban farm are made (e.g. no heat ventilation into the growing media to extend growing periods, etc.)
- Energy savings only apply to the floor directly below the roof. This will underestimate the energy savings to the entire building, since the attenuation of temperature shifts on the top floor will have a spillover effect on energy use on subsequent floors that diminishes with distance from the roof.
- We assume that the energy impacts of rooftop urban farming are similar to those from extensive green roofs.
- Effects at the city level are modeled in an additive manner, ignoring the multiplicative effect of large numbers of farms in proximity. This will underestimate total energy savings as reduced air conditioning use from an attenuated urban heat island effect are not counted here.
- Insulation values and heating fuels are assumed to be independent of other building characteristics (e.g. age, height, size, etc.) during the Monte Carlo simulations, as the building energy surveys lack data on relating these characteristics for the New England region.

Modeling building energy savings start first by characterizing the level of insulation on the building and the energy consumption per unit area for heating and cooling. Both of these parameters are taken from the residential and commercial building energy consumption surveys[25,32]. Heating and cooling energy intensities are assumed to be constant for all commercial and residential buildings in the city, while insulation levels are assigned probabilistically to each building at the start of each simulation. Likewise, the heating fuel and presence of air conditioning are assigned in the same manner to buildings that are lacking these data in the tax assessment survey. The prevalence of different heating types and air conditioning presence are also taken from the building energy surveys. Table S44 outlines these parameter values and their likelihood in the New England building stock.

Table S44. Building parameters

	Residential		Commercial	
Parameter	**Value**	**Probability**	**Value**	**Probability**
Energy Intensity				
Heating Intensity	352 MJ/m^2/a*	-	465 MJ/m^2/a	-
Cooling Intensity	6 MJ/m^2/a*	-	51 MJ/m^2/a	-
Insulation Levels				
Well	-	0.36	-	0.36**
Adequate	-	0.44	-	0.44**
Poor	-	0.2	-	0.2**
None	-	0	-	0**
Air Conditioning Present				
Yes	-	0.76	-	0.62
No	-	0.24	-	0.38
Heating Present				
Yes	-	1	-	0.87
No	-	0	-	0.13
Heating Fuel				
Electricity	-	0.12	-	0.18
Natural Gas	-	0.52	-	0.36
Fuel Oil	-	0.32	-	0.46
Propane	-	0.04	-	0

* Taken as the total energy intensity for residential buildings (Table CE1.2-RECS2009)[32] times the percentage going to different end uses[33]
** Not available in the commercial energy consumption survey. Assumed that same as residential values

To link UF with energy savings, a relation between insulation level and amount of cooling and heating attenuation is needed. Results from La Roche and Berardi's field work measuring energy savings of green roofs at different insulation thicknesses was useful in building this concordance[34]. In using their numbers we assume equivalent percentage savings for buildings in Chicago, US and Boston. Although Chicago has a continental climate with slightly warmer summers and cooler winters, the data adequate for the cursory analysis performed here. Table S45 outlines the concordance between the insulation levels here and the predicted energy savings from building-integrated UF.

Table S45. Predicted energy savings at different insulation levels

Insulation level from energy consumption survey	Insulation thickness from La Roche and Berardi (m)[34]	Heating attenuation (%)	Cooling Attenuation (%)
Well	0.20	0	7.5
Adequate	0.10	0	7.5
Poor	0.05	2.5	8
None	0	7.5	15

With these parameters in hand for each building, the UF related energy savings are estimated as the product of energy intensity, area and percentage attenuation. Embodied greenhouse gas impacts are taken from the Boston's own carbon footprint accounting since these represent the intensities for the local grid and fuel delivery systems[35]. Table S46 outlines emissions intensities for the different fuels used in Boston buildings for space conditioning.

Table S46. Carbon intensities for different fuels in Boston

Energy source	kg CO2e/MJ supplied
Electricity	0.102
Natural Gas	0.050
Fuel Oil	0.070
Propane*	0.050

* Assumed equivalent to natural gas here. Minor role in energy system should not influence general results.

City-wide optimization simulations

In assessing the impacts of UF at the city level, all of the disparate pieces described in the preceding sections were tied together. A Python 2.7 script acts as a scaffolding with which to model the impacts of UF on Boston's food-borne GWP impacts and land use, and to model interactions between the urban farms and the city's energy and material metabolism. The script can optimize UF in Boston to maximize any one of three indicators at a time: GWP savings, land use savings and nutritional content. As many of the building parameters were assigned probabilistically, we run each optimization scenario 100 times in a Monte Carlo manner, randomly assigning UF suitability and building energy use characteristics. Despite the low number of runs, little variation is seen around the mean for the results, hinting at the suitability of our choice of simulation length. Requests for the script can be made through the corresponding author. Figure 11 outlines the algorithm.

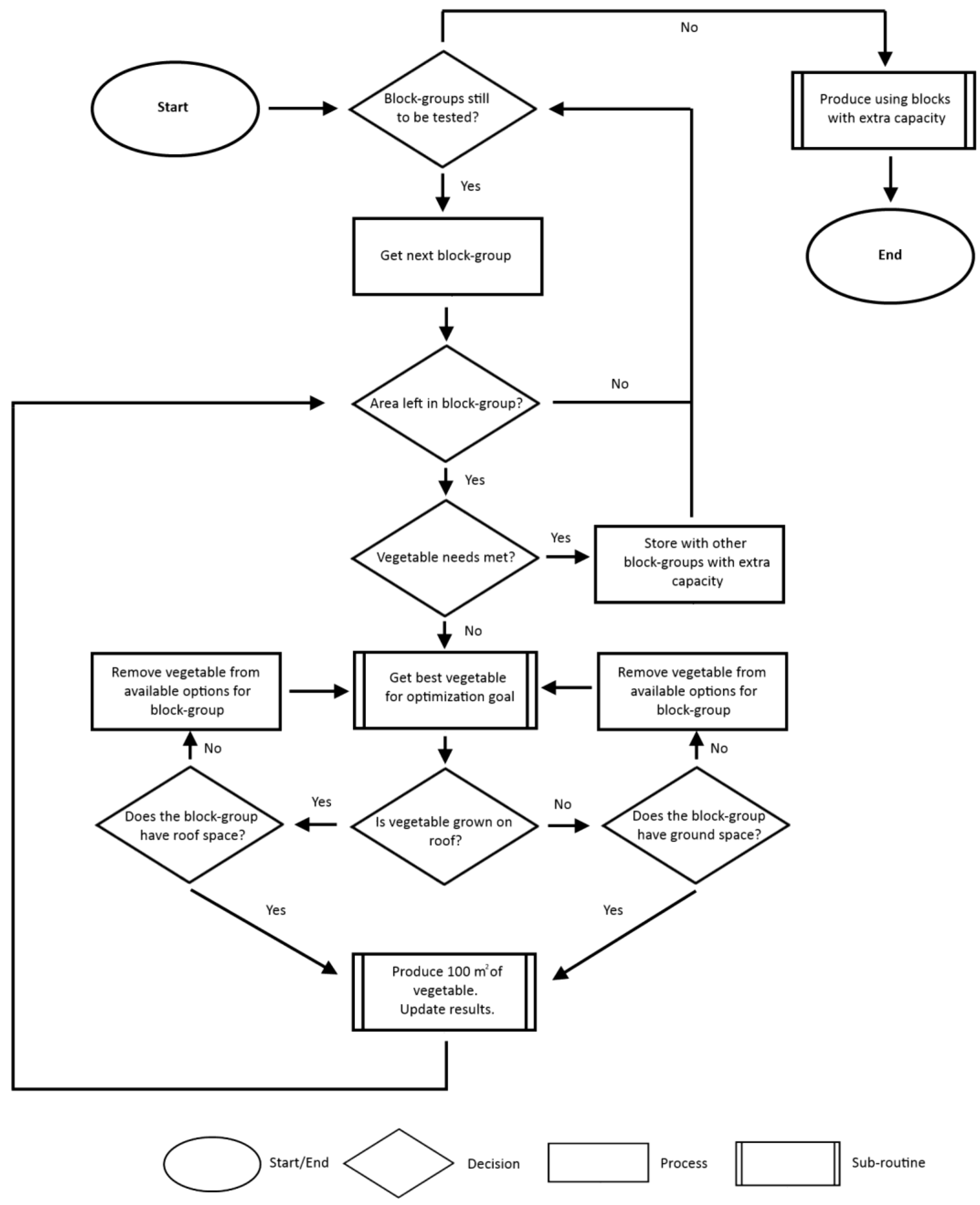


Figure 11. Optimization algorithm outline.

GWP Optimization

In optimizing the GWP impacts of the city's UF system, a 'greedy' algorithm is used. 'Greedy' algorithms work by picking items with the largest marginal benefit in terms of the parameter being optimized. In this case that means growing vegetables with the largest GWP impact reduction per unit area grown. Table S47 lists the UF produce with the largest reductions in GWP per area cultivated.

Table S47. List of UF vegetables in order of decreasing reductions in GWP impacts per m^2 planted

Vegetable	Siting
Kale	Ground
Eggplant	Ground
Green Beans	Ground
Tomato	Ground
Cucumber	Ground
Bell Pepper	Ground
Tomato	Roof
Turnip	Ground
Cucumber	Roof
Lettuce	Ground
Beet	Ground
Carrot	Ground
Scallion	Ground
Bell Pepper	Roof
Squash	Ground
Collard Greens	Ground
Cabbage	Ground
Radish	Roof
Lettuce	Roof
Carrot	Roof
Green Beans	Roof
Kale	Roof
Turnip	Roof
Scallion	Roof

Each run of the algorithm cycles through all of Boston's block groups and performs the following sub-routine for each individual block group:

<u>Block-group GWP optimizing sub-routine</u>

Is there area left in the block-group?

Yes: *Are the block-group's needs met for all vegetables?*

Yes: Store the block-group with others with extra capacity. End sub-routine.

No: Get the UF vegetable with the largest marginal GWP impact reduction.

Are all of the blocks needs met for this vegetable?

Yes: Remove vegetable from list of potential vegetables and get the next vegetable in the list.

No: *Where is the vegetable grown?*

Roof: *Is there building space?*

Yes: Produce 100 m^2 of the vegetable (or remainder of roof space if less than 100 m^2 left). Update results. Rerun sub-routine.

No: Remove vegetable from list of potential vegetables and attempt with next vegetable.

Ground: *Is there ground space?*

Yes: Produce 100 m^2 of the vegetable (or remainder of ground space if less than 100 m^2 left). Update results. Rerun sub-routine.

No: Remove vegetable from list of potential vegetables and attempt with next vegetable.

No: End sub-routine.

In this way each block-group will attempt to satisfy as much of its vegetable demands using those UF crops that minimize the GWP impacts of the block-group's residents. At the completion of a single cycle through all of Boston's block-groups, if there are block-groups that are able to satiate there vegetable demands while having surplus space, a separate sub-routine is run on those blocks:

City GWP optimizing sub-routine

Is there area left in the block?

Yes: *Are all of the city's needs met for all vegetables?*

Yes: End sub-routine.

No: Get the UF vegetable with the largest marginal GWP impact reduction.

Are all of the city's needs met for this vegetable?

Yes: Remove vegetable from list of potential vegetables and get the next vegetable in the list.

No: *Where is the vegetable grown?*

Roof: *Is there building space?*

Yes: Produce 100 m^2 of the vegetable (or remainder of roof space if less than 100 m^2 left). Update results. Rerun sub-routine.

No: Remove vegetable from list of potential vegetables and attempt with next vegetable.

Ground: *Is there ground space?*

Yes: Produce 100 m^2 of the vegetable (or remainder of ground space if less than 100 m^2 left). Update results. Rerun sub-routine.

No: Remove vegetable from list of potential vegetables and attempt with next vegetable.

No: End sub-routine.

This sub-routine is run on all of the block-groups with auxiliary space until all are exhausted or the city's vegetable needs are met. This algorithm can be run with additive or subtractive UF space estimates, including or excluding parking.

In determining the block-group and city-wide vegetable demands we use the 2010 LAFA data for average demands at the household prior to household wastage and multiply by the population for each block-group. This assumes that wastage from the urban farms is negligible, which was observed during in the field while working with the case farms. We do not attempt to satiate the needs for all vegetables listed in the USDA LAFA data[2], but only those that UF produces or where UF crops act as reasonable substitutes. Table S48 shows the average intake of relevant vegetables from the LAFA data.

Table S48. LAFA data and per capita demand of UF producible vegetables

Vegetable	Raw LAFA (lb/a)	Per capita demand of UF crop (kg/a)	Total Boston Demand (kg/a)	Fraction of total vegetables
Beans		2.31	1424548.816	0.045155
Fresh	1.44			
Canned	2.07			
Frozen	1.58			
Beet*	0.24	0.11	68551.87793	0.002173
Bell Pepper	8.77	3.98	2456900.259	0.077879
Cabbage		2.90	1786523.718	0.056629
Fresh	5.96			
Canned	0.41			
Carrots		3.83	2361388.616	0.074851
Fresh	7.14			
Canned	0.53			
Frozen	0.76			
Collard Greens	0.51	0.23	143684.5788	0.004555
Cucumbers		3.28	2023733.81	0.064148
Fresh	5.81			
Canned	1.41			
Eggplant	0.53	0.24	147267.9982	0.004668
Kale		0.89	549605.5795	0.017421
Kale	0.24			
Spinach	1.27			
Frozen Spinach	0.45			
Lettuce		10.52	6484207.704	0.205537
Leaf	13.52			
Romaine	9.62			
Radish	0.38	0.17	106540.9844	0.003377
Scallion	0.24	0.11	68551.87793	0.002173
Squash		3.13	1931088.178	0.061212
Squash	3.40			
Pumpkin	3.49			
Tomato		19.34	11926557.87	0.378048
Fresh	15.2			
Canned	27.4			
Turnip*	0.24	0.11	68551.87793	0.002173

* No LAFA data on beets and turnips. Assumed to be the same as the lowest consumed food for which LAFA data exists, Kale.

Land use optimization

This method is identical to the GWP impact algorithm except that UF crops are now listed in order of their ability to reduce land use. Table S49 shows the list of vegetables when ordered in this manner.

Table S49. List of UF vegetables in order of decreasing reductions in land use per m^2 planted

Vegetable	Siting
Green Beans	Ground
Radish	Roof
Kale	Ground
Cucumber	Roof
Green Beans	Roof
Turnip	Ground
Tomato	Roof
Turnip	Roof
Bell Pepper	Roof
Kale	Roof
Squash	Ground
Cucumber	Ground
Lettuce	Roof
Carrot	Roof
Cabbage	Ground
Scallion	Roof
Beet	Ground
Tomato	Ground
Collard Greens	Ground
Carrot	Ground
Scallion	Ground
Bell Pepper	Ground
Eggplant	Ground
Lettuce	Ground

Nutritional Optimization

In optimizing for nutrition, the algorithm is moved away from a greedy mode. This is because the boundary for knowing when to stop producing the best-option vegetable in the greedy mode is the demand for that crop at the block-group or city level. In the nutritional optimizing algorithm we are in fact attempting to change the boundary condition, that is, the amount of certain foods consumed, eliminating this indicators candidacy for this role. Instead we randomly pick vegetables in a manner that reflect the consumption patterns of the average consumer, whilst trying provide as much nutrition as possible, beyond their typical demands, aiming to satisfy the nutritional needs as outlined by the USDA guidelines[1].

USDA guidelines provide recommended intakes for four vegetable types: starchy, dark green, red and orange and other. Here we focus on the last three since none of the vegetables in the first group are produced by any of the case farms. The nutritional algorithm has two variants. The first attempts to produce as much vegetables as possible and satiate the entire vegetable demands of the block-group (and city using surplus land). The second version attempts to close the gap between current consumption and USDA guidelines. In both versions the vegetable group with the largest distance to target is always prioritized, so that in the first variant it will end up producing nearly the same fraction of USDA guidelines, while the second may or may not end up satisfying all groups to the same extent. Importantly, the second variant models a situation where UF is not substituting conventional supply chains, but supplementing, and hence, no crediting for avoided conventional production is accounted for.

Vegetable demands are taken from the USDA guidelines for different sexes and age groups. The deficiency is taken as the difference between the USDA guidelines and usual daily intake from the NHANES data[36]. Individual nutritional demands and deficiencies are then combined with census demographics data for each block-group to get the total demands at block-group and city level. Table S50 shows the nutritional demands and deficits for different demographics.

Table S50. Nutritional demands and deficits (in brackets) for different demographics

		Males								**Females**							
		Age								**Age**							
Vegetable Category	**Unit**	1-3	4-8	9-13	14-18	19-30	31-50	51-70	71+	1-3	4-8	9-13	14-18	19-30	31-50	51-70	71+
Dark Greens	cup eq.	0.5 (0.5)	1 (1)	1.5 (1.5)	2 (1.3)	2.5 (1.8)	2.5 (1.8)	2 (0.6)	2 (1.3)	1 (1)	1.5 (1.5)	1.5 (1.5)	1.5 (0.8)	1.5 (0.8)	1.5 (0.8)	1.5 (0.1)	1.5 (0.8)
Red and Orange	cup eq.	2.5 (1.1)	3 (0.9)	5.5 (3.4)	6 (3.6)	7 (3.5)	7 (3.5)	6 (3.2)	6 (3.2)	2.5 (1.1)	3 (1.6)	5.5 (3.4)	5.5 (3.4)	5.5 (2.7)	5.5 (2.7)	5.5 (2.7)	5.5 (2.7)
Other	cup eq.	1 (1.3)	3.5 (1.4)	5 (3.6)	6 (3.9)	7 (3.8)	7 (3.8)	6 (0.6)	6 (2.5)	2 (0.6)	3 (1.6)	5 (2.9)	5 (2.9)	5 (1.5)	5 (0.8)	5 (0.1)	5 (1.5)

Taking the institution adjusted population of Boston of 616,602 in 2010 and the demographic spread, we estimate the city-wide nutritional demands as 5.68×10^7, 1.83×10^8 and 1.75×10^8 cup eq. of dark green, red and orange, and other vegetables, respectively. City-wide nutritional deficits are estimated as 1.96×10^7, 6.64×10^8 and 2.62×10^7cup eq. for dark green, red and orange, and other vegetables, respectively.

Table S51 summarizes the UF crops in terms of their vegetable type and the amount of nutritional units supplied per area planted.

Table S51. UF Crops and their nutritional properties

Vegetable	USDA Category	Siting	Cup eq./m^2
Beans	Other	Ground	28
Beet	Other	Ground	17
Bell Pepper	Red and Orange	Ground	19
Cabbage	Other	Ground	52
Carrots	Red and Orange	Ground	13
Collard Greens	Dark Green	Ground	6
Cucumbers	Other	Ground	28
Eggplant	Other	Ground	28
Kale	Dark Green	Ground	36
Lettuce	Other	Ground	7
Squash	Other	Ground	22
Tomato	Red and Orange	Ground	17
Turnip	Other	Ground	27
Scallion	Other	Ground	8
Beans	Other	Roof	10
Bell Pepper	Red and Orange	Roof	20
Carrots	Red and Orange	Roof	13
Cucumbers	Other	Roof	44
Kale	Dark Green	Roof	10
Lettuce	Other	Roof	7
Radish	Other	Roof	25
Scallion	Other	Roof	9

Tomato	Red and Orange	Roof	28
Turnip	Other	Roof	14

Block-group nutritional optimization sub-routine

Is there area left in the block-group?

Yes: *Are the block-group's nutritional demands (or deficit) met?*

Yes: Store the block-group with others with extra capacity. End sub-routine.

No: Determine the vegetable type with largest distance to gap.

Is there building space?

Yes: Randomly choose vegetable from amongst those within the vegetable category that are grown on buildings, with probability based on usual intake rates. Produce 100 m^2 of the vegetable (or remainder of roof space if less than 100 m^2 left). Update results. Rerun sub-routine.

No: Randomly choose vegetable from amongst those within the vegetable category that are grown on the ground, with probability based on usual intake rates. Produce 100 m^2 of the vegetable (or remainder of roof space if less than 100 m^2 left). Update results. Rerun sub-routine.

No: End sub-routine.

After all block-groups are given the chance to produce for themselves, those with surplus growing area attempt to produce to satisfy Boston's nutritional needs.

City nutritional optimization sub-routine

Is there area left in the block-group?

Yes: *Are the city's nutritional demands (or deficit) met?*

Yes: End sub-routine.

No: Determine the vegetable type with largest distance to gap at the city level.

Is there building space?

Yes: Randomly choose vegetable from amongst those within the vegetable category that are grown on buildings, with probability based on usual intake rates. Produce 100 m^2 of the vegetable (or remainder of roof space if less than 100 m^2 left). Update results. Rerun sub-routine.

No: Randomly choose vegetable from amongst those within the vegetable category that are grown on the ground, with probability based on usual intake rates. Produce 100 m^2 of the vegetable (or remainder of roof space if less than 100 m^2 left). Update results. Rerun sub-routine.

No: End sub-routine.

In the same manner is the GWP and land use sub-routines, this algorithm can be used with additive and subtractive UF land use estimates.

UF Revenue

Crop prices are taken from consumer expenditure data (averaged over the available years)[37] or from USDA retail reports on specialty crops[38]. Table 49 outlines the crop prices used here in current US dollars.

Table S52. Crop prices

Vegetable	USD/kg	Source
Beans	3.20	Consumer Expenditure
Beet	2.19	USDA
Cabbage	1.42	Consumer Expenditure
Carrots	1.72	Consumer Expenditure
Collard Greens	2.13	USDA
Cucumbers	2.85	USDA
Eggplant	3.01	USDA
Iceberg	2.28	Consumer Expenditure
Kale	2.28	USDA
Peppers	5.38	Consumer Expenditure
Radish	3.51	USDA
Scallion	1.22	USDA
Squash	1.86	USDA
Tomato	3.71	Consumer Expenditure
Turnip	2.19	USDA

When the city only produces for its residents, the above algorithms are unaltered, and the revenue from block-group trade is calculated and recorded along with all of the environmental and nutritional results.

The only shift to the algorithm is when the block group starts exporting the conurbation. A crude method would simply produce the most profitable crop, but this would actually lead to a glut of one or two crops on the market, leading to a crash in prices. To avoid this, the city's extra space is allocated to crops based on the usual demand for the crop according to the USDA LAFA data (see rightmost column of Table 45). The above algorithms remain unaltered from the above cases with the exception of a sub-routine that is run at the end on all block-groups with surplus land:

Is there area left in the block-group?

Yes: Randomly select vegetable based on usual intake probability.

Is there suitable UF space to grow the crop (either roof or ground)?

Yes: Grow 100 m^2 (or available area) of that vegetable and update results. Rerun sub-routine.

No: End sub-routine.

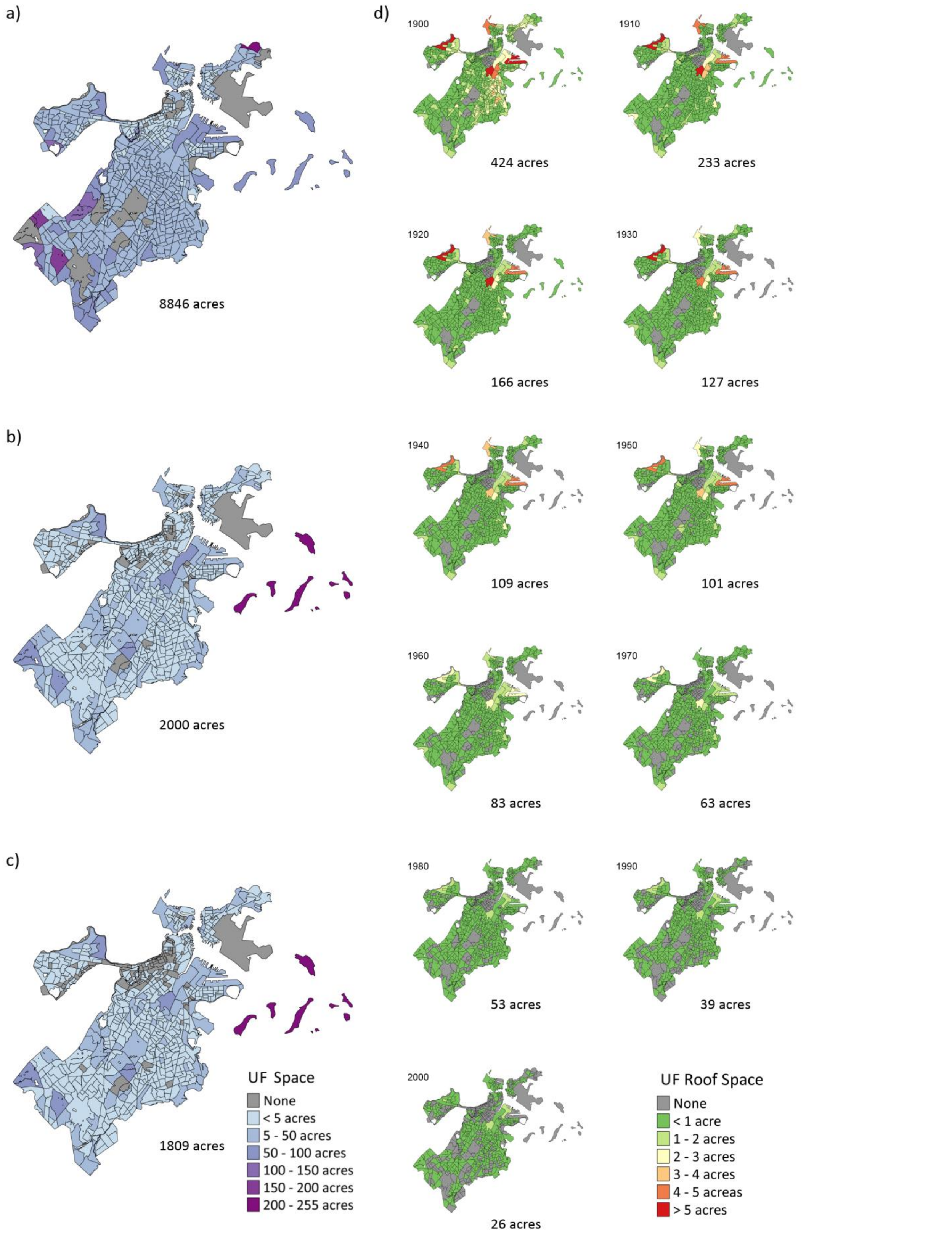


Figure 12. UF space results for (a) subtractive, (b) additive, (c) additive minus parking and (d) rooftop

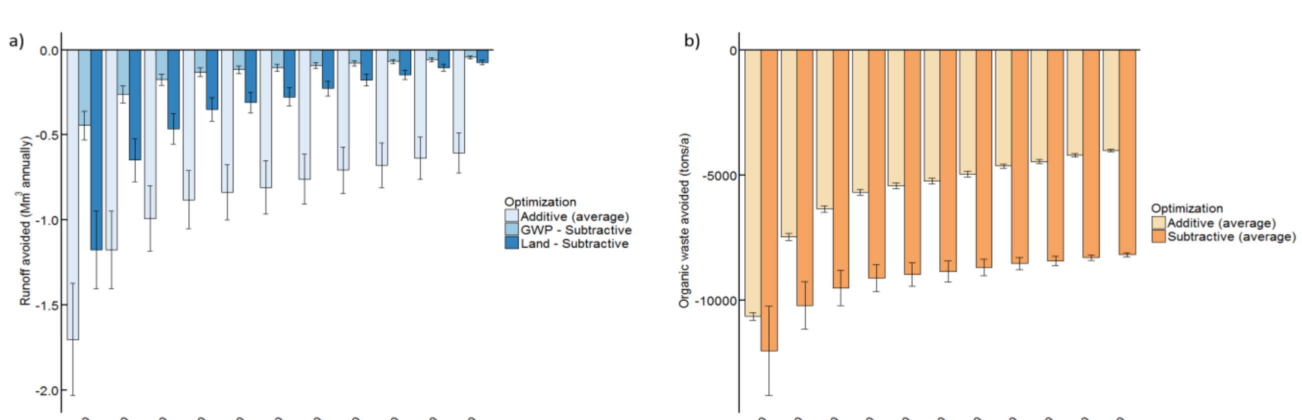


Figure 13. (a) avoided runoff results for the different scenarios and years . Additive results for both land and GWP are averaged due to similarity. (b) Organic waste uptake from UF averaged for both optimizations due to similarity.

Raw Results

Table S53 - GWP optimization where UF space was estimated with an additive method.

Table S54 - GWP optimization where UF space was estimated with an additive method, but excluding parking.

Table S55 - GWP optimization where UF space was estimated with a subtractive method.

Table S56 - GWP optimization where UF space was estimated with a subtractive method with vegetable exporting

Table S57 – Land use optimization where UF space was estimated with an additive method.

Table S58 – Land use optimization where UF space was estimated with an additive method, but excluding parking.

Table S59 – Land use optimization where UF space was estimated with a subtractive method.

Table S60 – Land use optimization where UF space was estimated with a subtractive method with vegetable exporting

Table S61 – Nutritional needs optimization where UF space was estimated with an additive method.

Table S62 – Nutritional needs optimization where UF space was estimated with an additive method, but excluding parking.

Table S63 – Nutritional deficit optimization where UF space was estimated with an additive method, but excluding parking.

Table S64 – Nutritional needs optimization where UF space was estimated with a subtractive method.

Table S65 – Nutritional needs optimization where UF space was estimated with a subtractive method with vegetable exporting

Table S53. GWP Optimized – Additive

Cutoff Year	GHG Shift (kg CO_2e/a)	SD	Building Energy (kg CO_2e/a)	SD	Land Use Shift (m^2/a)	SD	Runoff Reduction(m^3/a) - high	SD	Runoff Reduction (m^3/a) - low	SD	Waste Uptake (kg/a)	SD	Greens Produced (cup eq./a)	SD	Red and Orange Produced (cup eq./a)	SD	Other Produced (cup eq./a)	SD	Planted Area (m^2/a)	SD	Roof Area (m^2)	SD	Revenue (USD/a)	SD
1900	-1.92E+07	6.89E+04	3.19E+06	9.20E+04	8.32E+06	1.67E+04	-2.04E+06	3.09E+04	-1.38E+06	2.08E+04	1.07E+07	1.56E+05	4.41E+06	0.00E+00	9.28E+07	4.33E+04	6.13E+07	3.21E+05	9.69E+06	3.77E+04	1.71E+06	3.77E+04	2.63E+07	2.63E+05
1910	-1.85E+07	6.17E+04	1.85E+06	8.64E+04	7.71E+06	3.27E+04	-1.40E+06	2.92E+04	-9.49E+05	1.97E+04	7.47E+06	1.47E+05	4.41E+06	0.00E+00	9.26E+07	3.71E+04	5.45E+07	3.09E+05	8.91E+06	3.56E+04	9.42E+05	3.56E+04	3.17E+07	2.66E+05
1920	-1.82E+07	6.02E+04	1.36E+06	7.75E+04	7.42E+06	3.41E+04	-1.18E+06	2.53E+04	-8.00E+05	1.71E+04	6.36E+06	1.28E+05	4.41E+06	0.00E+00	9.25E+07	3.39E+04	5.19E+07	2.78E+05	8.65E+06	3.09E+04	6.73E+05	3.09E+04	3.43E+07	2.15E+05
1930	-1.81E+07	5.38E+04	1.05E+06	7.11E+04	7.23E+06	3.61E+04	-1.05E+06	2.36E+04	-7.11E+05	1.60E+04	5.69E+06	1.19E+05	4.41E+06	0.00E+00	9.26E+07	1.14E+05	5.03E+07	2.64E+05	8.48E+06	2.89E+04	5.12E+05	2.89E+04	3.58E+07	2.08E+05
1940	-1.80E+07	4.53E+04	9.08E+05	6.53E+04	7.14E+06	3.86E+04	-9.96E+05	2.04E+04	-6.73E+05	1.38E+04	5.41E+06	1.03E+05	4.41E+06	0.00E+00	9.25E+07	3.01E+04	4.97E+07	2.40E+05	8.42E+06	2.49E+04	4.43E+05	2.49E+04	3.63E+07	2.25E+05
1950	-1.80E+07	5.08E+04	8.30E+05	7.51E+04	7.10E+06	3.46E+04	-9.65E+05	2.45E+04	-6.52E+05	1.65E+04	5.25E+06	1.23E+05	4.41E+06	0.00E+00	9.25E+07	2.75E+04	4.94E+07	2.81E+05	8.38E+06	2.99E+04	4.05E+05	2.99E+04	3.66E+07	2.08E+05
1960	-1.79E+07	4.36E+04	6.75E+05	6.44E+04	7.03E+06	3.48E+04	-9.06E+05	2.15E+04	-6.12E+05	1.45E+04	4.95E+06	1.09E+05	4.41E+06	0.00E+00	9.25E+07	4.00E+04	4.87E+07	2.59E+05	8.31E+06	2.63E+04	3.33E+05	2.63E+04	3.68E+07	1.90E+05
1970	-1.78E+07	3.55E+04	5.20E+05	5.03E+04	6.94E+06	3.06E+04	-8.46E+05	1.82E+04	-5.71E+05	1.23E+04	4.65E+06	9.19E+04	4.41E+06	0.00E+00	9.25E+07	5.16E+04	4.79E+07	2.08E+05	8.23E+06	2.22E+04	2.60E+05	2.22E+04	3.72E+07	1.83E+05
1980	-1.77E+07	3.10E+04	4.23E+05	4.58E+04	6.89E+06	3.06E+04	-8.09E+05	1.66E+04	-5.46E+05	1.12E+04	4.46E+06	8.38E+04	4.41E+06	0.00E+00	9.24E+07	4.35E+04	4.75E+07	2.11E+05	8.19E+06	2.03E+04	2.15E+05	2.03E+04	3.74E+07	1.83E+05
1990	-1.77E+07	2.57E+04	3.00E+05	3.83E+04	6.82E+06	3.07E+04	-7.60E+05	1.26E+04	-5.13E+05	8.52E+03	4.22E+06	6.36E+04	4.41E+06	0.00E+00	9.24E+07	3.64E+04	4.69E+07	1.88E+05	8.13E+06	1.54E+04	1.55E+05	1.54E+04	3.78E+07	1.53E+05
2000	-1.76E+07	2.10E+04	2.09E+05	2.97E+04	6.78E+06	2.71E+04	-7.22E+05	9.81E+03	-4.88E+05	6.63E+03	4.02E+06	4.95E+04	4.41E+06	0.00E+00	9.24E+07	2.29E+04	4.63E+07	1.86E+05	8.08E+06	1.20E+04	1.09E+05	1.20E+04	3.81E+07	1.30E+05

Table S54. GWP Optimized – Additive, no parking

Cutoff Year	GHG Shift (kg CO_2e/a)	SD	Building Energy (kg CO_2e/a)	SD	Land Use Shift (m^2/a)	SD	Runoff Reduction(m^3/a) - high	SD	Runoff Reduction (m^3/a) - low	SD	Waste Uptake (kg/a)	SD	Greens Produced (cup eq./a)	SD	Red and Orange Produced (cup eq./a)	SD	Other Produced (cup eq./a)	SD	Planted Area (m^2/a)	SD	Roof Area (m^2)	SD	Revenue (USD/a)	SD
1900	-1.92E+07	6.16E+04	8.31E+06	2.12E+04	-2.03E+06	3.04E+04	-1.37E+06	2.05E+04	4.41E+06	9.31E-10	9.28E+07	4.28E+04	6.12E+07	3.09E+05	9.68E+06	3.71E+04	2.63E+07	2.70E+05	1.07E+07	1.53E+05	3.19E+06	8.56E+04	1.71E+06	3.71E+04
1910	-1.85E+07	6.87E+04	7.72E+06	3.27E+04	-1.40E+06	3.17E+04	-9.48E+05	2.14E+04	4.41E+06	9.31E-10	9.26E+07	3.92E+04	5.45E+07	3.40E+05	8.91E+06	3.87E+04	3.17E+07	2.91E+05	7.46E+06	1.60E+05	1.86E+06	9.57E+04	9.40E+05	3.87E+04
1920	-1.82E+07	6.09E+04	7.41E+06	3.52E+04	-1.18E+06	2.43E+04	-7.99E+05	1.64E+04	4.41E+06	9.31E-10	9.25E+07	3.68E+04	5.19E+07	2.69E+05	8.64E+06	2.96E+04	3.43E+07	2.20E+05	6.35E+06	1.23E+05	1.35E+06	7.92E+04	6.71E+05	2.96E+04
1930	-1.81E+07	5.86E+04	7.24E+06	3.61E+04	-1.05E+06	2.48E+04	-7.11E+05	1.68E+04	4.41E+06	9.31E-10	9.26E+07	1.25E+05	5.04E+07	2.71E+05	8.48E+06	3.03E+04	3.58E+07	2.33E+05	5.69E+06	1.25E+05	1.04E+06	7.73E+04	5.13E+05	3.03E+04
1940	-1.80E+07	5.08E+04	7.16E+06	3.59E+04	-1.00E+06	2.35E+04	-6.77E+05	1.59E+04	4.41E+06	9.31E-10	9.25E+07	3.26E+04	4.98E+07	2.70E+05	8.42E+06	2.87E+04	3.62E+07	2.20E+05	5.44E+06	1.19E+05	9.25E+05	7.26E+04	4.51E+05	2.87E+04
1950	-1.80E+07	4.52E+04	7.10E+06	2.53E+04	-9.65E+05	2.24E+04	-6.52E+05	1.51E+04	4.41E+06	9.31E-10	9.25E+07	3.21E+04	4.93E+07	2.44E+05	8.38E+06	2.73E+04	3.66E+07	1.95E+05	5.25E+06	1.13E+05	8.35E+05	6.79E+04	4.06E+05	2.73E+04
1960	-1.79E+07	3.58E+04	7.03E+06	3.29E+04	-9.07E+05	1.88E+04	-6.13E+05	1.27E+04	4.41E+06	9.31E-10	9.25E+07	4.04E+04	4.87E+07	2.29E+05	8.31E+06	2.30E+04	3.69E+07	1.87E+05	4.96E+06	9.51E+04	6.78E+05	5.37E+04	3.34E+05	2.30E+04
1970	-1.78E+07	3.53E+04	6.94E+06	3.43E+04	-8.45E+05	1.66E+04	-5.71E+05	1.12E+04	4.41E+06	9.31E-10	9.25E+07	4.61E+04	4.79E+07	2.05E+05	8.23E+06	2.03E+04	3.72E+07	1.99E+05	4.65E+06	8.38E+04	5.21E+05	4.91E+04	2.59E+05	2.03E+04
1980	-1.77E+07	2.99E+04	6.89E+06	3.22E+04	-8.08E+05	1.64E+04	-5.46E+05	1.11E+04	4.41E+06	9.31E-10	9.24E+07	3.66E+04	4.75E+07	2.17E+05	8.19E+06	2.00E+04	3.74E+07	1.86E+05	4.46E+06	8.29E+04	4.25E+05	4.46E+04	2.14E+05	2.00E+04
1990	-1.77E+07	2.41E+04	6.82E+06	3.00E+04	-7.60E+05	1.36E+04	-5.14E+05	9.16E+03	4.41E+06	9.31E-10	9.24E+07	3.16E+04	4.69E+07	2.00E+05	8.13E+06	1.65E+04	3.78E+07	1.63E+05	4.22E+06	6.84E+04	3.02E+05	3.67E+04	1.56E+05	1.65E+04

2000	-1.76E+07	2.05E+04	6.78E+06	2.71E+04	-7.22E+05	1.18E+04	-4.88E+05	7.98E+03	4.41E+06	9.31E-10	9.24E+07	3.01E+04	4.64E+07	2.01E+05	8.08E+06	1.44E+04	3.81E+07	1.45E+05	4.03E+06	5.96E+04	2.11E+05	3.20E+04	1.09E+05	1.44E+04

Table S55. GWP Optimized – Subtractive

Cutoff Year	GHG Shift (kg CO_2e/a)	SD	Building Energy (kg CO_2e/a)	SD	Land Use Shift (m^2/a)	SD	Runoff Reduction(m^3/a) - high	SD	Runoff Reduction (m^3/a) - low	SD	Waste Uptake (kg/a)	SD	Greens Produced (cup eq./a)	SD	Red and Orange Produced (cup eq./a)	SD	Other Produced (cup eq./a)	SD	Planted Area (m^2/a)	SD	Roof Area (m^2)	SD	Revenue (USD/a)	SD
1900	-2.43E+07	2.23E+04	2.52E+07	3.10E+04	-5.32E+05	9.09E+03	-3.59E+05	6.14E+03	6.29E+06	1.09E+02	1.10E+08	1.28E+04	1.30E+08	9.10E+03	1.75E+07	4.55E+03	1.31E+07	1.50E+05	1.02E+07	4.01E+04	1.20E+06	3.14E+04	6.49E+05	1.11E+04
1910	-2.43E+07	1.94E+04	2.57E+07	3.11E+04	-3.13E+05	1.28E+04	-2.11E+05	8.67E+03	6.29E+06	6.02E+01	1.10E+08	7.14E+02	1.30E+08	1.73E+04	1.75E+07	3.64E+03	1.39E+07	1.34E+05	9.26E+06	5.70E+04	7.37E+05	3.89E+04	3.82E+05	1.57E+04
1920	-2.43E+07	1.91E+04	2.59E+07	3.60E+04	-2.10E+05	1.24E+04	-1.42E+05	8.38E+03	6.29E+06	2.79E-09	1.10E+08	3.07E+03	1.30E+08	1.99E+04	1.75E+07	4.27E+03	1.47E+07	1.24E+05	8.81E+06	5.50E+04	5.05E+05	3.57E+04	2.56E+05	1.51E+04
1930	-2.43E+07	1.85E+04	2.61E+07	3.06E+04	-1.58E+05	1.06E+04	-1.07E+05	7.16E+03	6.29E+06	2.79E-09	1.10E+08	7.74E+03	1.30E+08	1.86E+04	1.75E+07	3.48E+03	1.51E+07	9.82E+04	8.58E+06	4.72E+04	3.84E+05	3.23E+04	1.93E+05	1.29E+04
1940	-2.43E+07	1.58E+04	2.61E+07	3.19E+04	-1.40E+05	1.11E+04	-9.43E+04	7.50E+03	6.29E+06	2.79E-09	1.10E+08	3.36E+03	1.30E+08	1.85E+04	1.75E+07	3.22E+03	1.51E+07	1.12E+05	8.50E+06	4.95E+04	3.42E+05	3.23E+04	1.70E+05	1.36E+04
1950	-2.43E+07	1.76E+04	2.62E+07	2.97E+04	-1.25E+05	1.04E+04	-8.47E+04	7.05E+03	6.29E+06	2.79E-09	1.10E+08	4.66E+03	1.30E+08	1.98E+04	1.76E+07	3.55E+03	1.52E+07	1.11E+05	8.43E+06	4.62E+04	3.03E+05	2.99E+04	1.53E+05	1.27E+04
1960	-2.43E+07	1.40E+04	2.62E+07	3.17E+04	-1.10E+05	1.07E+04	-7.43E+04	7.25E+03	6.29E+06	2.79E-09	1.10E+08	7.75E+02	1.30E+08	1.63E+04	1.76E+07	2.90E+03	1.53E+07	1.04E+05	8.37E+06	4.77E+04	2.60E+05	2.78E+04	1.34E+05	1.31E+04
1970	-2.43E+07	1.35E+04	2.62E+07	2.54E+04	-9.40E+04	8.48E+03	-6.35E+04	5.73E+03	6.29E+06	2.79E-09	1.10E+08	8.31E+02	1.30E+08	3.35E+04	1.76E+07	2.90E+03	1.54E+07	8.73E+04	8.29E+06	3.77E+04	2.22E+05	2.45E+04	1.15E+05	1.04E+04
1980	-2.43E+07	1.30E+04	2.63E+07	2.38E+04	-8.20E+04	7.82E+03	-5.54E+04	5.28E+03	6.29E+06	2.79E-09	1.10E+08	1.31E+03	1.30E+08	6.14E+04	1.76E+07	3.30E+03	1.55E+07	6.74E+04	8.24E+06	3.55E+04	1.94E+05	2.42E+04	1.00E+05	9.55E+03
1990	-2.43E+07	1.57E+04	2.63E+07	2.71E+04	-6.97E+04	8.54E+03	-4.71E+04	5.77E+03	6.29E+06	2.79E-09	1.10E+08	8.60E+02	1.30E+08	8.85E+04	1.76E+07	3.90E+03	1.56E+07	6.49E+04	8.19E+06	3.91E+04	1.61E+05	2.43E+04	8.50E+04	1.04E+04
2000	-2.43E+07	1.40E+04	2.64E+07	1.76E+04	-5.22E+04	5.64E+03	-3.53E+04	3.81E+03	6.29E+06	2.79E-09	1.10E+08	8.18E+02	1.30E+08	5.91E+04	1.76E+07	2.60E+03	1.57E+07	4.23E+04	8.11E+06	2.56E+04	1.22E+05	2.08E+04	6.38E+04	6.88E+03

Table S56. GWP Optimized – Subtractive, with exporting

Cutoff Year	GHG Shift (kg CO_2e/a)	SD	Building Energy (kg CO_2e/a)	SD	Land Use Shift (m^2/a)	SD	Runoff Reductio n(m^3/a) - high	SD	Runoff Reductio n (m^3/a) - low	SD	Waste Uptake (kg/a)	SD	Greens Produced (cup eq./a)	SD	Red and Orange Produced (cup eq./a)	SD	Other Produced (cup eq./a)	SD	Planted Area (m^2/a)	SD	Roof Area (m^2)	SD	Revenue (USD/a)	SD	Export (USD/a)	SD
1900	-5.93E+07	1.13E+05	4.10E+07	6.92E+04	-1.40E+06	2.72E+04	-9.49E+05	1.84E+04	1.90E+07	1.91E+05	2.96E+08	7.53E+05	3.08E+08	7.06E+05	3.74E+07	3.32E+04	1.69E+08	4.36E+05	2.31E+07	1.37E+05	3.19E+06	8.09E+04	1.71E+06	3.32E+04	1.56E+08	4.60E+05
1910	-5.77E+07	1.14E+05	4.17E+07	6.35E+04	-7.69E+05	2.97E+04	-5.20E+05	2.00E+04	1.88E+07	2.00E+05	2.86E+08	8.29E+05	3.02E+08	7.07E+05	3.67E+07	3.62E+04	1.63E+08	4.68E+05	1.99E+07	1.50E+05	1.85E+06	8.78E+04	9.39E+05	3.62E+04	1.49E+08	4.74E+05
1920	-5.72E+07	1.07E+05	4.19E+07	8.24E+04	-5.52E+05	2.41E+04	-3.73E+05	1.63E+04	1.86E+07	1.95E+05	2.83E+08	7.01E+05	3.01E+08	7.98E+05	3.64E+07	2.95E+04	1.61E+08	4.23E+05	1.88E+07	1.22E+05	1.36E+06	7.38E+04	6.74E+05	2.95E+04	1.46E+08	4.38E+05
1930	-5.68E+07	1.04E+05	4.20E+07	7.35E+04	-4.22E+05	2.52E+04	-2.85E+05	1.70E+04	1.86E+07	2.27E+05	2.81E+08	6.89E+05	2.99E+08	7.88E+05	3.63E+07	3.08E+04	1.59E+08	4.42E+05	1.82E+07	1.27E+05	1.05E+06	7.39E+04	5.15E+05	3.08E+04	1.44E+08	4.51E+05
1940	-5.67E+07	1.06E+05	4.21E+07	7.36E+04	-3.65E+05	2.46E+04	-2.47E+05	1.66E+04	1.85E+07	2.24E+05	2.80E+08	7.05E+05	2.99E+08	7.38E+05	3.62E+07	3.00E+04	1.59E+08	4.34E+05	1.79E+07	1.24E+05	9.14E+05	6.90E+04	4.46E+05	3.00E+04	1.44E+08	4.33E+05
1950	-5.65E+07	1.05E+05	4.21E+07	6.10E+04	-3.29E+05	2.59E+04	-2.22E+05	1.75E+04	1.85E+07	2.13E+05	2.79E+08	7.13E+05	2.98E+08	7.68E+05	3.61E+07	3.16E+04	1.58E+08	4.03E+05	1.77E+07	1.31E+05	8.17E+05	7.97E+04	4.02E+05	3.16E+04	1.43E+08	4.11E+05
1960	-5.64E+07	8.11E+04	4.22E+07	7.32E+04	-2.77E+05	2.00E+04	-1.87E+05	1.35E+04	1.85E+07	1.96E+05	2.78E+08	5.73E+05	2.98E+08	7.79E+05	3.61E+07	2.44E+04	1.58E+08	3.51E+05	1.74E+07	1.01E+05	6.83E+05	5.60E+04	3.38E+05	2.44E+04	1.43E+08	3.41E+05
1970	-5.62E+07	8.49E+04	4.22E+07	5.63E+04	-2.12E+05	1.92E+04	-1.43E+05	1.30E+04	1.84E+07	2.00E+05	2.77E+08	5.42E+05	2.98E+08	6.96E+05	3.60E+07	2.34E+04	1.57E+08	3.22E+05	1.71E+07	9.69E+04	5.18E+05	5.32E+04	2.59E+05	2.34E+04	1.42E+08	3.21E+05
1980	-5.61E+07	7.74E+04	4.23E+07	6.50E+04	-1.76E+05	1.55E+04	-1.19E+05	1.04E+04	1.84E+07	2.01E+05	2.77E+08	4.61E+05	2.97E+08	6.74E+05	3.60E+07	1.89E+04	1.57E+08	2.75E+05	1.69E+07	7.80E+04	4.29E+05	4.48E+04	2.15E+05	1.89E+04	1.41E+08	2.83E+05
1990	-5.60E+07	6.73E+04	4.23E+07	6.30E+04	-1.29E+05	1.33E+04	-8.73E+04	8.96E+03	1.84E+07	2.10E+05	2.76E+08	5.02E+05	2.97E+08	6.30E+05	3.59E+07	1.62E+04	1.56E+08	2.56E+05	1.67E+07	6.70E+04	3.05E+05	3.68E+04	1.58E+05	1.62E+04	1.41E+08	2.53E+05
2000	-5.58E+07	6.39E+04	4.24E+07	6.58E+04	-8.79E+04	1.13E+04	-5.94E+04	7.65E+03	1.84E+07	2.28E+05	2.75E+08	4.45E+05	2.96E+08	7.05E+05	3.58E+07	1.38E+04	1.56E+08	2.33E+05	1.65E+07	5.72E+04	2.04E+05	3.20E+04	1.07E+05	1.38E+04	1.40E+08	2.32E+05

Table S57. Land Optimized – Additive

Cutoff Year	GHG Shift (kg CO_2e/a)	SD	Building Energy (kg CO_2e/a)	SD	Land Use Shift (m^2/a)	SD	Runoff Reduction(m^3/a) - high	SD	Runoff Reduction (m^3/a) - low	SD	Waste Uptake (kg/a)	SD	Greens Produced (cup eq./a)	SD	Red and Orange Produced (cup eq./a)	SD	Other Produced (cup eq./a)	SD	Planted Area (m^2/a)	SD	Roof Area (m^2)	SD	Revenue (USD/a)	SD
1900	-1.67E+07	9.73E+04	3.17E+06	8.20E+04	4.44E+06	2.31E+04	-2.03E+06	2.81E+04	-1.37E+06	1.90E+04	1.06E+07	1.42E+05	6.29E+06	9.83E+02	1.08E+08	7.34E+05	7.77E+07	1.42E+05	9.68E+06	3.43E+04	1.71E+06	3.43E+04	3.13E+07	2.63E+05
1910	-1.51E+07	5.24E+04	1.86E+06	8.62E+04	4.12E+06	2.16E+04	-1.41E+06	2.89E+04	-9.50E+05	1.95E+04	7.48E+06	1.46E+05	6.29E+06	1.23E+03	9.19E+07	5.22E+05	7.59E+07	1.46E+05	8.92E+06	3.53E+04	9.44E+05	3.53E+04	3.00E+07	2.15E+05
1920	-1.50E+07	5.33E+04	1.36E+06	8.44E+04	4.14E+06	2.26E+04	-1.18E+06	2.72E+04	-7.99E+05	1.84E+04	6.35E+06	1.37E+05	6.29E+06	6.25E+02	8.72E+07	5.61E+05	7.55E+07	1.07E+05	8.64E+06	3.32E+04	6.71E+05	3.32E+04	3.18E+07	2.00E+05
1930	-1.49E+07	5.12E+04	1.04E+06	8.04E+04	4.14E+06	2.21E+04	-1.05E+06	2.60E+04	-7.10E+05	1.76E+04	5.69E+06	1.31E+05	6.29E+06	1.87E+02	8.44E+07	5.38E+05	7.53E+07	1.84E+05	8.48E+06	3.18E+04	5.11E+05	3.18E+04	3.28E+07	2.03E+05
1940	-1.49E+07	4.58E+04	9.14E+05	7.70E+04	4.15E+06	1.86E+04	-1.00E+06	2.60E+04	-6.77E+05	1.76E+04	5.44E+06	1.31E+05	6.29E+06	2.10E+02	8.34E+07	5.50E+05	7.52E+07	1.19E+05	8.42E+06	3.18E+04	4.51E+05	3.18E+04	3.32E+07	2.26E+05
1950	-1.49E+07	4.11E+04	8.32E+05	6.94E+04	4.15E+06	1.62E+04	-9.65E+05	2.30E+04	-6.52E+05	1.55E+04	5.25E+06	1.16E+05	6.29E+06	1.83E+02	8.26E+07	5.14E+05	7.51E+07	8.90E+04	8.38E+06	2.80E+04	4.05E+05	2.80E+04	3.34E+07	2.03E+05
1960	-1.48E+07	3.47E+04	6.81E+05	6.43E+04	4.16E+06	1.12E+04	-9.09E+05	2.11E+04	-6.14E+05	1.43E+04	4.97E+06	1.07E+05	6.29E+06	1.77E+02	8.15E+07	4.88E+05	7.50E+07	5.44E+04	8.31E+06	2.58E+04	3.37E+05	2.58E+04	3.37E+07	2.08E+05
1970	-1.48E+07	2.46E+04	5.17E+05	4.89E+04	4.16E+06	9.50E+03	-8.43E+05	1.77E+04	-5.70E+05	1.20E+04	4.64E+06	8.94E+04	6.29E+06	1.57E+02	8.00E+07	4.25E+05	7.49E+07	4.28E+04	8.23E+06	2.16E+04	2.57E+05	2.16E+04	3.41E+07	1.62E+05
1980	-1.48E+07	2.31E+04	4.23E+05	4.19E+04	4.15E+06	8.10E+03	-8.09E+05	1.43E+04	-5.47E+05	9.64E+03	4.46E+06	7.20E+04	6.29E+06	1.82E+02	7.92E+07	3.46E+05	7.49E+07	4.64E+04	8.19E+06	1.74E+04	2.15E+05	1.74E+04	3.44E+07	1.59E+05
1990	-1.48E+07	1.78E+04	3.01E+05	3.51E+04	4.14E+06	1.50E+04	-7.60E+05	1.31E+04	-5.14E+05	8.84E+03	4.22E+06	6.60E+04	6.29E+06	1.77E+02	7.80E+07	3.13E+05	7.49E+07	9.91E+04	8.13E+06	1.60E+04	1.55E+05	1.60E+04	3.48E+07	1.51E+05
2000	-1.48E+07	1.43E+04	2.10E+05	3.11E+04	4.14E+06	1.13E+04	-7.23E+05	1.09E+04	-4.88E+05	7.34E+03	4.03E+06	5.48E+04	6.28E+06	1.65E+04	7.71E+07	2.21E+05	7.49E+07	8.46E+04	8.08E+06	1.33E+04	1.10E+05	1.33E+04	3.51E+07	1.10E+05

Table S58. Land Optimized – Additive, no parking

Cutoff Year	GHG Shift (kg CO_2e/a)	SD	Building Energy (kg CO_2e/a)	SD	Land Use Shift (m^2/a)	SD	Runoff Reduction(m^3/a) - high	SD	Runoff Reduction (m^3/a) - low	SD	Waste Uptake (kg/a)	SD	Greens Produced (cup eq./a)	SD	Red and Orange Produced (cup eq./a)	SD	Other Produced (cup eq./a)	SD	Planted Area (m^2/a)	SD	Roof Area (m^2)	SD	Revenue (USD/a)	SD
1900	-1.67E+07	1.10E+05	4.44E+06	2.07E+04	-2.03E+06	3.15E+04	-1.37E+06	2.13E+04	6.29E+06	1.02E+03	1.08E+08	8.17E+05	7.77E+07	1.23E+05	9.68E+06	3.84E+04	3.13E+07	3.00E+05	1.06E+07	1.59E+05	3.17E+06	9.28E+04	1.71E+06	3.84E+04
1910	-1.51E+07	4.47E+04	4.12E+06	2.22E+04	-1.40E+06	2.58E+04	-9.48E+05	1.75E+04	6.29E+06	1.07E+03	9.18E+07	5.09E+05	7.59E+07	1.10E+05	8.91E+06	3.15E+04	2.99E+07	2.29E+05	7.46E+06	1.30E+05	1.86E+06	7.09E+04	9.40E+05	3.15E+04
1920	-1.50E+07	6.00E+04	4.14E+06	1.80E+04	-1.19E+06	2.90E+04	-8.01E+05	1.96E+04	6.29E+06	5.98E+02	8.73E+07	5.78E+05	7.55E+07	1.16E+05	8.65E+06	3.54E+04	3.17E+07	1.92E+05	6.37E+06	1.46E+05	1.37E+06	8.83E+04	6.75E+05	3.54E+04
1930	-1.49E+07	5.04E+04	4.15E+06	2.03E+04	-1.05E+06	2.62E+04	-7.09E+05	1.77E+04	6.29E+06	2.32E+02	8.44E+07	5.26E+05	7.53E+07	1.55E+05	8.48E+06	3.20E+04	3.28E+07	1.89E+05	5.68E+06	1.32E+05	1.04E+06	7.89E+04	5.09E+05	3.20E+04
1940	-1.49E+07	4.62E+04	4.15E+06	1.93E+04	-1.00E+06	2.47E+04	-6.77E+05	1.67E+04	6.29E+06	1.73E+02	8.34E+07	5.22E+05	7.53E+07	1.40E+05	8.42E+06	3.02E+04	3.31E+07	2.03E+05	5.44E+06	1.25E+05	9.24E+05	7.04E+04	4.51E+05	3.02E+04
1950	-1.49E+07	4.19E+04	4.15E+06	1.78E+04	-9.62E+05	2.56E+04	-6.50E+05	1.73E+04	6.29E+06	1.80E+02	8.25E+07	6.00E+05	7.51E+07	7.42E+04	8.37E+06	3.12E+04	3.34E+07	2.20E+05	5.24E+06	1.29E+05	8.20E+05	7.34E+04	4.02E+05	3.12E+04
1960	-1.48E+07	3.34E+04	4.16E+06	1.31E+04	-9.06E+05	2.11E+04	-6.12E+05	1.43E+04	6.29E+06	1.58E+02	8.14E+07	4.94E+05	7.50E+07	6.31E+04	8.31E+06	2.58E+04	3.36E+07	2.21E+05	4.95E+06	1.07E+05	6.73E+05	6.23E+04	3.34E+05	2.58E+04
1970	-1.48E+07	2.88E+04	4.16E+06	1.03E+04	-8.40E+05	1.95E+04	-5.68E+05	1.32E+04	6.29E+06	1.72E+02	7.99E+07	4.70E+05	7.50E+07	5.29E+04	8.23E+06	2.39E+04	3.41E+07	2.05E+05	4.62E+06	9.87E+04	5.07E+05	5.86E+04	2.53E+05	2.39E+04
1980	-1.48E+07	2.19E+04	4.15E+06	9.68E+03	-8.11E+05	1.59E+04	-5.48E+05	1.08E+04	6.29E+06	1.73E+02	7.92E+07	3.97E+05	7.49E+07	5.43E+04	8.19E+06	1.95E+04	3.44E+07	1.69E+05	4.47E+06	8.05E+04	4.30E+05	4.64E+04	2.17E+05	1.95E+04
1990	-1.48E+07	1.87E+04	4.14E+06	1.30E+04	-7.59E+05	1.32E+04	-5.13E+05	8.90E+03	6.29E+06	1.56E+02	7.80E+07	3.27E+05	7.49E+07	8.90E+04	8.13E+06	1.61E+04	3.48E+07	1.49E+05	4.21E+06	6.65E+04	2.99E+05	4.00E+04	1.54E+05	1.61E+04
2000	-1.48E+07	1.71E+04	4.14E+06	1.19E+04	-7.22E+05	1.02E+04	-4.88E+05	6.88E+03	6.28E+06	1.73E+04	7.71E+07	2.10E+05	7.49E+07	9.36E+04	8.08E+06	1.24E+04	3.52E+07	1.06E+05	4.02E+06	5.14E+04	2.10E+05	2.86E+04	1.08E+05	1.24E+04

Table S59. Land Optimized – Subtractive

Cutoff Year	GHG Shift (kg CO_2e/a)	SD	Building Energy (kg CO_2e/a)	SD	Land Use Shift (m^2/a)	SD	Runoff Reduction(m^3/a) - high	SD	Runoff Reduction (m^3/a) - low	SD	Waste Uptake (kg/a)	SD	Greens Produced (cup eq./a)	SD	Red and Orange Produced (cup eq./a)	SD	Other Produced (cup eq./a)	SD	Planted Area (m^2/a)	SD	Roof Area (m^2)	SD	Revenue (USD/a)	SD
1900	-2.34E+07	3.44E+04	2.28E+07	7.38E+04	-1.40E+06	2.66E+04	-9.48E+05	1.79E+04	6.29E+06	6.79E+02	1.10E+08	8.72E+02	1.30E+08	4.84E+04	1.67E+07	1.40E+04	1.24E+07	2.59E+05	1.38E+07	1.15E+05	3.19E+06	7.59E+04	1.71E+06	3.24E+04
1910	-2.38E+07	3.91E+04	2.45E+07	7.91E+04	-7.75E+05	2.87E+04	-5.23E+05	1.94E+04	6.29E+06	1.79E+02	1.10E+08	7.98E+02	1.30E+08	6.47E+04	1.71E+07	1.61E+04	1.37E+07	2.75E+05	1.11E+07	1.24E+05	1.86E+06	8.44E+04	9.45E+05	3.50E+04
1920	-2.40E+07	3.87E+04	2.51E+07	6.93E+04	-5.53E+05	2.59E+04	-3.74E+05	1.75E+04	6.29E+06	1.62E+02	1.10E+08	8.84E+02	1.30E+08	5.58E+04	1.72E+07	1.59E+04	1.46E+07	2.52E+05	1.02E+07	1.11E+05	1.37E+06	8.14E+04	6.75E+05	3.16E+04
1930	-2.40E+07	3.76E+04	2.55E+07	7.03E+04	-4.19E+05	2.52E+04	-2.83E+05	1.70E+04	6.29E+06	1.57E+02	1.10E+08	7.88E+02	1.30E+08	8.19E+04	1.73E+07	1.55E+04	1.50E+07	2.61E+05	9.65E+06	1.08E+05	1.04E+06	7.25E+04	5.11E+05	3.08E+04
1940	-2.41E+07	3.33E+04	2.56E+07	7.23E+04	-3.71E+05	2.66E+04	-2.50E+05	1.80E+04	6.29E+06	1.63E+02	1.10E+08	8.79E+02	1.30E+08	7.35E+04	1.73E+07	1.53E+04	1.52E+07	2.25E+05	9.45E+06	1.14E+05	9.29E+05	7.53E+04	4.52E+05	3.25E+04
1950	-2.41E+07	3.65E+04	2.57E+07	6.86E+04	-3.30E+05	2.55E+04	-2.23E+05	1.73E+04	6.29E+06	1.50E+02	1.10E+08	8.32E+02	1.30E+08	9.21E+04	1.74E+07	1.50E+04	1.53E+07	2.48E+05	9.27E+06	1.09E+05	8.25E+05	8.02E+04	4.03E+05	3.12E+04
1960	-2.41E+07	3.22E+04	2.58E+07	5.59E+04	-2.72E+05	2.08E+04	-1.84E+05	1.40E+04	6.29E+06	1.67E+02	1.10E+08	7.60E+02	1.30E+08	1.09E+05	1.74E+07	1.49E+04	1.55E+07	1.82E+05	9.03E+06	8.74E+04	6.68E+05	6.58E+04	3.32E+05	2.54E+04
1970	-2.41E+07	2.47E+04	2.60E+07	4.41E+04	-2.13E+05	1.70E+04	-1.44E+05	1.15E+04	6.29E+06	1.75E+02	1.10E+08	8.79E+02	1.30E+08	4.95E+04	1.74E+07	1.16E+04	1.58E+07	1.56E+05	8.78E+06	7.14E+04	5.24E+05	5.22E+04	2.60E+05	2.07E+04
1980	-2.41E+07	2.28E+04	2.61E+07	3.57E+04	-1.75E+05	1.45E+04	-1.18E+05	9.79E+03	6.29E+06	1.75E+02	1.10E+08	8.75E+02	1.30E+08	5.95E+04	1.75E+07	1.09E+04	1.61E+07	1.06E+05	8.62E+06	6.06E+04	4.23E+05	4.15E+04	2.14E+05	1.77E+04
1990	-2.42E+07	2.06E+04	2.62E+07	3.16E+04	-1.27E+05	1.29E+04	-8.59E+04	8.72E+03	6.29E+06	1.55E+02	1.10E+08	8.68E+02	1.30E+08	1.06E+05	1.75E+07	1.07E+04	1.63E+07	7.39E+04	8.42E+06	5.44E+04	2.98E+05	3.71E+04	1.55E+05	1.58E+04
2000	-2.42E+07	1.66E+04	2.63E+07	2.75E+04	-8.95E+04	1.08E+04	-6.05E+04	7.27E+03	6.29E+06	1.80E+02	1.10E+08	6.83E+02	1.30E+08	9.02E+04	1.75E+07	6.87E+03	1.64E+07	4.17E+04	8.26E+06	4.64E+04	2.12E+05	3.27E+04	1.09E+05	1.31E+04

Table S60. Land Optimized – Subtractive, with exporting

Cutoff Year	GHG Shift (kg CO_2e/a)	SD	Building Energy (kg CO_2e/a)	SD	Land Use Shift (m^2/a)	SD	Runoff Reductio n(m^3/a) - high	SD	Runoff Reductio n (m^3/a) - low	SD	Waste Uptake (kg/a)	SD	Greens Produced (cup eq./a)	SD	Red and Orange Produced (cup eq./a)	SD	Other Produced (cup eq./a)	SD	Planted Area (m^2/a)	SD	Roof Area (m^2)	SD	Revenue (USD/a)	SD	Export (USD/a)	SD
1900	-5.91E+07	1.05E+05	4.10E+07	7.56E+04	-1.40E+06	2.40E+04	-9.45E+05	1.62E+04	2.00E+07	1.96E+05	2.97E+08	5.63E+05	3.19E+08	8.22E+05	3.74E+07	2.93E+04	1.71E+08	3.41E+05	2.31E+07	1.21E+05	3.18E+06	7.54E+04	1.71E+06	2.93E+04	1.59E+08	3.95E+05
1910	-5.76E+07	1.10E+05	4.18E+07	7.81E+04	-7.71E+05	3.32E+04	-5.21E+05	2.25E+04	1.93E+07	2.31E+05	2.87E+08	6.22E+05	3.08E+08	8.23E+05	3.67E+07	4.06E+04	1.64E+08	3.08E+05	1.99E+07	1.68E+05	1.86E+06	8.91E+04	9.42E+05	4.06E+04	1.50E+08	4.71E+05
1920	-5.70E+07	9.02E+04	4.20E+07	6.39E+04	-5.45E+05	2.89E+04	-3.68E+05	1.96E+04	1.90E+07	2.25E+05	2.83E+08	5.88E+05	3.04E+08	6.96E+05	3.64E+07	3.53E+04	1.62E+08	3.21E+05	1.88E+07	1.46E+05	1.34E+06	7.91E+04	6.66E+05	3.53E+04	1.47E+08	3.94E+05
1930	-5.67E+07	1.01E+05	4.21E+07	7.61E+04	-4.22E+05	2.37E+04	-2.85E+05	1.60E+04	1.89E+07	2.35E+05	2.81E+08	5.86E+05	3.03E+08	7.04E+05	3.63E+07	2.89E+04	1.60E+08	3.07E+05	1.82E+07	1.20E+05	1.05E+06	7.41E+04	5.15E+05	2.89E+04	1.45E+08	3.88E+05
1940	-5.66E+07	8.08E+04	4.22E+07	6.18E+04	-3.64E+05	2.38E+04	-2.46E+05	1.61E+04	1.88E+07	1.93E+05	2.80E+08	4.83E+05	3.01E+08	6.97E+05	3.62E+07	2.91E+04	1.60E+08	2.58E+05	1.79E+07	1.20E+05	9.03E+05	6.78E+04	4.44E+05	2.91E+04	1.44E+08	3.30E+05
1950	-5.65E+07	8.76E+04	4.22E+07	7.36E+04	-3.37E+05	2.15E+04	-2.28E+05	1.45E+04	1.87E+07	1.98E+05	2.80E+08	5.63E+05	3.01E+08	8.14E+05	3.61E+07	2.62E+04	1.59E+08	2.97E+05	1.77E+07	1.08E+05	8.41E+05	6.17E+04	4.12E+05	2.62E+04	1.44E+08	3.84E+05
1960	-5.63E+07	6.32E+04	4.23E+07	6.96E+04	-2.71E+05	1.84E+04	-1.83E+05	1.25E+04	1.87E+07	2.11E+05	2.79E+08	4.57E+05	3.00E+08	8.19E+05	3.61E+07	2.25E+04	1.59E+08	2.28E+05	1.74E+07	9.31E+04	6.67E+05	5.36E+04	3.31E+05	2.25E+04	1.43E+08	2.89E+05
1970	-5.61E+07	6.92E+04	4.23E+07	6.20E+04	-2.11E+05	1.74E+04	-1.42E+05	1.17E+04	1.86E+07	2.07E+05	2.77E+08	4.29E+05	2.99E+08	6.85E+05	3.60E+07	2.12E+04	1.58E+08	2.37E+05	1.71E+07	8.77E+04	5.17E+05	5.45E+04	2.57E+05	2.12E+04	1.42E+08	2.91E+05
1980	-5.61E+07	6.23E+04	4.24E+07	6.92E+04	-1.79E+05	1.41E+04	-1.21E+05	9.55E+03	1.86E+07	1.89E+05	2.77E+08	4.65E+05	2.98E+08	7.41E+05	3.60E+07	1.73E+04	1.58E+08	2.24E+05	1.69E+07	7.14E+04	4.33E+05	4.18E+04	2.18E+05	1.73E+04	1.42E+08	2.71E+05
1990	-5.59E+07	6.08E+04	4.24E+07	6.73E+04	-1.29E+05	1.11E+04	-8.75E+04	7.50E+03	1.85E+07	2.42E+05	2.76E+08	3.70E+05	2.98E+08	5.87E+05	3.59E+07	1.36E+04	1.57E+08	2.07E+05	1.67E+07	5.60E+04	3.08E+05	3.28E+04	1.58E+05	1.36E+04	1.41E+08	2.30E+05
2000	-5.58E+07	5.15E+04	4.24E+07	5.56E+04	-8.87E+04	1.19E+04	-5.99E+04	8.04E+03	1.84E+07	2.01E+05	2.75E+08	3.82E+05	2.97E+08	5.95E+05	3.58E+07	1.45E+04	1.57E+08	1.77E+05	1.65E+07	6.01E+04	2.09E+05	3.31E+04	1.08E+05	1.45E+04	1.40E+08	1.96E+05

Table S61. Nutrient Demand Optimized – Additive

Cutoff Year	GHG Shift (kg CO_2e/a)	SD	Building Energy (kg CO_2e/a)	SD	Land Use Shift (m^2/a)	SD	Runoff Reduction(m^3/a) - high	SD	Runoff Reduction (m^3/a) - low	SD	Waste Uptake (kg/a)	SD	Greens Produced (cup eq./a)	SD	Red and Orange Produced (cup eq./a)	SD	Other Produced (cup eq./a)	SD	Planted Area (m^2/a)	SD	Roof Area (m^2)	SD	Revenue (USD/a)	SD
1900	-1.76E+07	1.03E+05	3.19E+06	9.10E+04	4.82E+06	5.08E+04	-2.04E+06	2.90E+04	-1.38E+06	1.96E+04	1.07E+07	1.46E+05	2.54E+07	1.15E+05	8.19E+07	3.84E+05	7.81E+07	3.73E+05	9.68E+06	3.54E+04	1.71E+06	3.54E+04	2.85E+07	2.71E+05
1910	-1.65E+07	9.41E+04	1.85E+06	8.84E+04	5.25E+06	5.17E+04	-1.40E+06	2.73E+04	-9.48E+05	1.84E+04	7.46E+06	1.38E+05	2.36E+07	1.05E+05	7.62E+07	3.32E+05	7.27E+07	3.22E+05	8.91E+06	3.33E+04	9.39E+05	3.33E+04	2.83E+07	2.32E+05
1920	-1.61E+07	9.64E+04	1.37E+06	8.63E+04	5.39E+06	5.19E+04	-1.19E+06	2.68E+04	-8.02E+05	1.81E+04	6.37E+06	1.35E+05	2.30E+07	1.03E+05	7.43E+07	3.37E+05	7.09E+07	3.08E+05	8.65E+06	3.27E+04	6.76E+05	3.27E+04	2.81E+07	2.60E+05
1930	-1.57E+07	7.86E+04	1.05E+06	7.10E+04	5.49E+06	4.62E+04	-1.05E+06	2.51E+04	-7.13E+05	1.70E+04	5.70E+06	1.27E+05	2.26E+07	1.08E+05	7.30E+07	3.43E+05	6.97E+07	3.27E+05	8.49E+06	3.06E+04	5.15E+05	3.06E+04	2.79E+07	2.85E+05
1940	-1.56E+07	8.37E+04	9.13E+05	7.21E+04	5.53E+06	5.04E+04	-1.00E+06	2.54E+04	-6.76E+05	1.72E+04	5.43E+06	1.28E+05	2.25E+07	9.72E+04	7.26E+07	3.56E+05	6.92E+07	2.90E+05	8.42E+06	3.10E+04	4.48E+05	3.10E+04	2.78E+07	2.77E+05
1950	-1.56E+07	7.81E+04	8.33E+05	7.10E+04	5.57E+06	4.68E+04	-9.66E+05	2.34E+04	-6.53E+05	1.58E+04	5.26E+06	1.18E+05	2.24E+07	8.02E+04	7.22E+07	2.87E+05	6.89E+07	2.72E+05	8.38E+06	2.86E+04	4.07E+05	2.86E+04	2.78E+07	2.37E+05
1960	-1.54E+07	7.61E+04	6.69E+05	6.53E+04	5.60E+06	4.90E+04	-9.05E+05	2.10E+04	-6.11E+05	1.42E+04	4.95E+06	1.06E+05	2.22E+07	9.80E+04	7.17E+07	3.16E+05	6.83E+07	2.97E+05	8.30E+06	2.57E+04	3.32E+05	2.57E+04	2.76E+07	2.14E+05
1970	-1.53E+07	6.69E+04	5.17E+05	5.55E+04	5.65E+06	4.63E+04	-8.44E+05	1.99E+04	-5.70E+05	1.34E+04	4.64E+06	1.00E+05	2.20E+07	7.71E+04	7.11E+07	3.09E+05	6.78E+07	2.66E+05	8.23E+06	2.43E+04	2.57E+05	2.43E+04	2.74E+07	2.03E+05
1980	-1.52E+07	5.64E+04	4.27E+05	4.16E+04	5.67E+06	4.62E+04	-8.08E+05	1.46E+04	-5.46E+05	9.86E+03	4.46E+06	7.37E+04	2.19E+07	7.30E+04	7.07E+07	2.35E+05	6.75E+07	2.26E+05	8.19E+06	1.78E+04	2.14E+05	1.78E+04	2.72E+07	1.70E+05
1990	-1.51E+07	5.06E+04	2.97E+05	3.62E+04	5.71E+06	4.60E+04	-7.59E+05	1.32E+04	-5.13E+05	8.90E+03	4.21E+06	6.65E+04	2.17E+07	6.23E+04	7.02E+07	2.01E+05	6.70E+07	1.91E+05	8.13E+06	1.61E+04	1.53E+05	1.61E+04	2.71E+07	1.50E+05
2000	-1.50E+07	4.46E+04	2.14E+05	3.06E+04	5.74E+06	4.19E+04	-7.23E+05	1.06E+04	-4.89E+05	7.16E+03	4.03E+06	5.35E+04	2.16E+07	5.60E+04	6.99E+07	1.80E+05	6.66E+07	1.72E+05	8.08E+06	1.29E+04	1.11E+05	1.29E+04	2.70E+07	1.16E+05

Table S62. Nutrient Demand Optimized – Additive, no parking

Cutoff Year	GHG Shift (kg CO_2e/a)	SD	Building Energy (kg CO_2e/a)	SD	Land Use Shift (m^2/a)	SD	Runoff Reduction(m^3/a) - high	SD	Runoff Reduction (m^3/a) - low	SD	Waste Uptake (kg/a)	SD	Greens Produced (cup eq./a)	SD	Red and Orange Produced (cup eq./a)	SD	Other Produced (cup eq./a)	SD	Planted Area (m^2/a)	SD	Roof Area (m^2)	SD	Revenue (USD/a)	SD
1900	-1.76E+07	9.63E+04	4.82E+06	5.70E+04	-2.04E+06	2.65E+04	-1.38E+06	1.79E+04	2.54E+07	1.04E+05	8.19E+07	3.23E+05	7.82E+07	3.58E+05	9.69E+06	3.24E+04	2.86E+07	2.55E+05	1.07E+07	1.34E+05	3.20E+06	8.51E+04	1.72E+06	3.24E+04
1910	-1.65E+07	9.53E+04	5.26E+06	5.05E+04	-1.41E+06	2.97E+04	-9.51E+05	2.01E+04	2.36E+07	1.12E+05	7.63E+07	3.63E+05	7.27E+07	3.32E+05	8.92E+06	3.63E+04	2.83E+07	2.46E+05	7.48E+06	1.50E+05	1.87E+06	8.69E+04	9.45E+05	3.63E+04
1920	-1.60E+07	9.26E+04	5.40E+06	5.62E+04	-1.18E+06	2.76E+04	-8.00E+05	1.87E+04	2.30E+07	1.19E+05	7.42E+07	3.91E+05	7.08E+07	3.40E+05	8.64E+06	3.37E+04	2.80E+07	2.76E+05	6.36E+06	1.39E+05	1.36E+06	7.89E+04	6.73E+05	3.37E+04
1930	-1.57E+07	7.90E+04	5.50E+06	5.17E+04	-1.05E+06	2.67E+04	-7.10E+05	1.81E+04	2.26E+07	1.04E+05	7.30E+07	3.50E+05	6.96E+07	3.17E+05	8.48E+06	3.26E+04	2.79E+07	2.32E+05	5.69E+06	1.35E+05	1.04E+06	7.47E+04	5.10E+05	3.26E+04
1940	-1.56E+07	8.78E+04	5.53E+06	6.13E+04	-9.99E+05	2.50E+04	-6.75E+05	1.69E+04	2.24E+07	1.00E+05	7.25E+07	3.43E+05	6.92E+07	3.12E+05	8.42E+06	3.05E+04	2.78E+07	2.53E+05	5.42E+06	1.26E+05	9.17E+05	7.55E+04	4.47E+05	3.05E+04
1950	-1.55E+07	9.25E+04	5.56E+06	5.49E+04	-9.64E+05	2.58E+04	-6.51E+05	1.74E+04	2.23E+07	1.05E+05	7.22E+07	3.62E+05	6.89E+07	3.68E+05	8.38E+06	3.15E+04	2.77E+07	2.77E+05	5.25E+06	1.30E+05	8.22E+05	7.57E+04	4.04E+05	3.15E+04
1960	-1.54E+07	6.88E+04	5.60E+06	5.15E+04	-9.05E+05	1.86E+04	-6.12E+05	1.25E+04	2.22E+07	8.72E+04	7.17E+07	2.96E+05	6.84E+07	2.50E+05	8.30E+06	2.27E+04	2.75E+07	2.25E+05	4.95E+06	9.38E+04	6.75E+05	5.48E+04	3.33E+05	2.27E+04
1970	-1.53E+07	6.33E+04	5.65E+06	4.42E+04	-8.42E+05	1.64E+04	-5.69E+05	1.11E+04	2.20E+07	8.30E+04	7.10E+07	2.67E+05	6.77E+07	2.43E+05	8.23E+06	2.00E+04	2.74E+07	1.82E+05	4.63E+06	8.26E+04	5.13E+05	5.01E+04	2.55E+05	2.00E+04
1980	-1.52E+07	5.29E+04	5.68E+06	4.51E+04	-8.09E+05	1.32E+04	-5.47E+05	8.94E+03	2.19E+07	6.37E+04	7.07E+07	2.07E+05	6.75E+07	1.92E+05	8.19E+06	1.62E+04	2.72E+07	1.57E+05	4.46E+06	6.68E+04	4.27E+05	3.87E+04	2.15E+05	1.62E+04
1990	-1.51E+07	4.90E+04	5.71E+06	3.93E+04	-7.61E+05	1.37E+04	-5.14E+05	9.28E+03	2.17E+07	6.20E+04	7.02E+07	2.00E+05	6.70E+07	1.91E+05	8.13E+06	1.68E+04	2.71E+07	1.43E+05	4.22E+06	6.93E+04	3.02E+05	3.64E+04	1.56E+05	1.68E+04
2000	-1.50E+07	4.55E+04	5.75E+06	3.91E+04	-7.21E+05	1.13E+04	-4.87E+05	7.66E+03	2.16E+07	5.95E+04	6.98E+07	1.93E+05	6.66E+07	1.84E+05	8.08E+06	1.38E+04	2.70E+07	1.23E+05	4.02E+06	5.73E+04	2.05E+05	3.09E+04	1.07E+05	1.38E+04

Table S63. Nutrient Deficit Optimized – Additive, no parking

Cutoff Year	GHG Shift (kg CO_2e/a)	SD	Building Energy (kg CO_2e/a)	SD	Land Use Shift (m^2/a)	SD	Runoff Reduction(m^3/a) - high	SD	Runoff Reduction (m^3/a) - low	SD	Waste Uptake (kg/a)	SD	Greens Produced (cup eq./a)	SD	Red and Orange Produced (cup eq./a)	SD	Other Produced (cup eq./a)	SD	Planted Area (m^2/a)	SD	Roof Area (m^2)	SD	Revenue (USD/a)	SD
1900	3.36E+06	2.27E+04	9.57E+06	4.33E+04	-1.36E+06	1.91E+04	-9.16E+05	1.29E+04	1.96E+07	9.66E+02	6.64E+07	4.86E+02	2.62E+07	1.36E+03	5.87E+06	1.66E+04	1.68E+07	2.21E+05	6.98E+06	8.64E+04	2.15E+06	5.15E+04	1.18E+06	2.31E+04
1910	3.05E+06	2.76E+04	1.02E+07	3.80E+04	-9.50E+05	1.45E+04	-6.42E+05	9.78E+03	1.96E+07	1.22E+04	6.64E+07	2.92E+04	2.62E+07	2.95E+04	5.82E+06	1.67E+04	2.07E+07	2.00E+05	5.06E+06	7.17E+04	1.29E+06	4.45E+04	6.66E+05	1.88E+04
1920	2.95E+06	2.60E+04	1.04E+07	4.30E+04	-7.92E+05	1.23E+04	-5.35E+05	8.29E+03	1.96E+07	3.95E+03	6.64E+07	1.03E+04	2.62E+07	5.36E+03	5.79E+06	1.61E+04	2.21E+07	2.33E+05	4.27E+06	7.40E+04	9.00E+05	4.60E+04	4.54E+05	1.99E+04
1930	2.92E+06	2.75E+04	1.06E+07	4.28E+04	-7.15E+05	1.58E+04	-4.83E+05	1.07E+04	1.96E+07	2.81E+03	6.64E+07	2.56E+03	2.62E+07	3.37E+04	5.77E+06	1.67E+04	2.30E+07	1.80E+05	3.86E+06	7.69E+04	6.89E+05	4.64E+04	3.44E+05	2.05E+04
1940	2.90E+06	2.25E+04	1.06E+07	3.73E+04	-6.88E+05	1.14E+04	-4.65E+05	7.67E+03	1.96E+07	1.19E+04	6.64E+07	3.09E+04	2.62E+07	2.67E+04	5.77E+06	1.56E+04	2.33E+07	1.59E+05	3.69E+06	6.24E+04	6.05E+05	3.97E+04	2.99E+05	1.63E+04
1950	2.90E+06	2.67E+04	1.06E+07	3.91E+04	-6.69E+05	1.41E+04	-4.52E+05	9.55E+03	1.96E+07	9.25E+03	6.64E+07	6.86E+03	2.62E+07	4.07E+04	5.77E+06	1.56E+04	2.35E+07	1.84E+05	3.59E+06	7.03E+04	5.46E+05	4.66E+04	2.71E+05	1.87E+04
1960	2.89E+06	2.07E+04	1.07E+07	4.05E+04	-6.39E+05	1.50E+04	-4.32E+05	1.01E+04	1.96E+07	1.06E+03	6.64E+07	1.02E+03	2.62E+07	2.29E+03	5.77E+06	1.55E+04	2.37E+07	1.67E+05	3.44E+06	7.15E+04	4.66E+05	4.34E+04	2.33E+05	1.91E+04
1970	2.88E+06	2.31E+04	1.07E+07	3.99E+04	-6.03E+05	1.36E+04	-4.08E+05	9.19E+03	1.96E+07	1.02E+03	6.64E+07	8.08E+02	2.62E+07	1.42E+03	5.76E+06	1.36E+04	2.40E+07	1.78E+05	3.27E+06	6.51E+04	3.69E+05	4.25E+04	1.87E+05	1.76E+04
1980	2.88E+06	1.95E+04	1.08E+07	3.69E+04	-5.83E+05	1.27E+04	-3.94E+05	8.56E+03	1.96E+07	1.09E+03	6.64E+07	6.30E+02	2.62E+07	3.53E+03	5.76E+06	1.37E+04	2.41E+07	1.64E+05	3.17E+06	5.97E+04	3.18E+05	3.98E+04	1.60E+05	1.62E+04
1990	2.87E+06	1.51E+04	1.08E+07	3.38E+04	-5.49E+05	1.05E+04	-3.71E+05	7.11E+03	1.96E+07	1.14E+03	6.64E+07	6.08E+03	2.62E+07	2.69E+03	5.76E+06	1.15E+04	2.44E+07	1.46E+05	3.02E+06	4.61E+04	2.28E+05	2.95E+04	1.17E+05	1.26E+04
2000	2.86E+06	1.38E+04	1.09E+07	3.35E+04	-5.19E+05	9.27E+03	-3.51E+05	6.26E+03	1.96E+07	1.13E+03	6.64E+07	4.37E+03	2.62E+07	1.42E+03	5.76E+06	1.19E+04	2.46E+07	1.34E+05	2.88E+06	4.13E+04	1.56E+05	2.82E+04	8.11E+04	1.13E+04

Table S64. Nutrient Deficit Optimized – Additive, no parking

Cutoff Year	GHG Shift (kg CO_2e/a)	SD	Building Energy (kg CO_2e/a)	SD	Land Use Shift (m^2/a)	SD	Runoff Reduction(m^3/a) - high	SD	Runoff Reduction (m^3/a) - low	SD	Waste Uptake (kg/a)	SD	Greens Produced (cup eq./a)	SD	Red and Orange Produced (cup eq./a)	SD	Other Produced (cup eq./a)	SD	Planted Area (m^2/a)	SD	Roof Area (m^2)	SD	Revenue (USD/a)	SD
1900	-3.93E+07	4.99E+04	1.43E+07	7.41E+04	-8.21E+05	1.63E+04	-5.55E+05	1.10E+04	5.68E+07	2.13E+03	1.83E+08	2.87E+03	1.75E+08	1.39E+03	2.14E+07	2.85E+04	4.60E+07	1.89E+05	1.33E+07	7.73E+04	1.85E+06	4.81E+04	1.00E+06	1.99E+04
1910	-3.94E+07	5.29E+04	1.48E+07	7.85E+04	-4.46E+05	1.73E+04	-3.02E+05	1.17E+04	5.68E+07	1.14E+03	1.83E+08	4.19E+03	1.75E+08	7.36E+03	2.13E+07	2.44E+04	4.81E+07	1.65E+05	1.16E+07	8.12E+04	1.07E+06	5.04E+04	5.45E+05	2.11E+04
1920	-3.93E+07	5.33E+04	1.50E+07	8.39E+04	-3.07E+05	1.44E+04	-2.08E+05	9.75E+03	5.68E+07	1.03E+03	1.83E+08	1.87E+03	1.75E+08	2.15E+03	2.13E+07	2.81E+04	4.88E+07	1.73E+05	1.09E+07	6.64E+04	7.50E+05	4.04E+04	3.75E+05	1.76E+04
1930	-3.93E+07	5.28E+04	1.51E+07	7.61E+04	-2.32E+05	1.52E+04	-1.57E+05	1.03E+04	5.68E+07	1.06E+03	1.83E+08	4.97E+02	1.75E+08	1.25E+03	2.12E+07	2.64E+04	4.92E+07	1.49E+05	1.06E+07	7.03E+04	5.71E+05	4.34E+04	2.83E+05	1.86E+04
1940	-3.93E+07	4.80E+04	1.52E+07	8.34E+04	-1.99E+05	1.47E+04	-1.35E+05	9.91E+03	5.68E+07	1.12E+03	1.83E+08	6.23E+02	1.75E+08	1.35E+03	2.12E+07	2.64E+04	4.93E+07	1.26E+05	1.04E+07	6.71E+04	4.94E+05	4.11E+04	2.43E+05	1.79E+04
1950	-3.93E+07	4.78E+04	1.52E+07	7.35E+04	-1.81E+05	1.60E+04	-1.22E+05	1.08E+04	5.68E+07	1.10E+03	1.83E+08	4.92E+02	1.75E+08	1.10E+03	2.12E+07	2.47E+04	4.94E+07	1.74E+05	1.03E+07	7.18E+04	4.46E+05	4.91E+04	2.21E+05	1.95E+04
1960	-3.93E+07	4.78E+04	1.53E+07	8.32E+04	-1.52E+05	1.33E+04	-1.02E+05	8.98E+03	5.68E+07	1.14E+03	1.83E+08	5.13E+02	1.75E+08	1.14E+03	2.12E+07	2.57E+04	4.95E+07	1.25E+05	1.02E+07	6.13E+04	3.68E+05	3.89E+04	1.85E+05	1.62E+04
1970	-3.93E+07	4.68E+04	1.53E+07	8.09E+04	-1.19E+05	1.18E+04	-8.02E+04	7.98E+03	5.68E+07	1.12E+03	1.83E+08	5.20E+02	1.75E+08	1.41E+03	2.12E+07	2.50E+04	4.97E+07	1.57E+05	1.01E+07	5.44E+04	2.85E+05	3.49E+04	1.45E+05	1.44E+04
1980	-3.93E+07	4.87E+04	1.53E+07	8.43E+04	-1.03E+05	8.77E+03	-6.97E+04	5.93E+03	5.68E+07	1.04E+03	1.83E+08	5.14E+02	1.75E+08	1.36E+03	2.12E+07	2.59E+04	4.97E+07	1.31E+05	9.98E+06	4.04E+04	2.46E+05	2.50E+04	1.26E+05	1.07E+04
1990	-3.93E+07	5.19E+04	1.54E+07	6.96E+04	-7.66E+04	8.50E+03	-5.18E+04	5.74E+03	5.68E+07	1.09E+03	1.83E+08	5.21E+02	1.75E+08	1.21E+03	2.12E+07	2.06E+04	4.98E+07	1.33E+05	9.86E+06	3.77E+04	1.78E+05	2.46E+04	9.35E+04	1.04E+04
2000	-3.93E+07	4.08E+04	1.54E+07	7.82E+04	-5.35E+04	7.96E+03	-3.62E+04	5.38E+03	5.68E+07	1.09E+03	1.83E+08	4.80E+02	1.75E+08	1.42E+03	2.12E+07	2.04E+04	5.00E+07	1.14E+05	9.76E+06	3.69E+04	1.26E+05	2.32E+04	6.53E+04	9.72E+03

Table S65. Nutrition Optimized – Subtractive, with exporting

Cutoff Year	GHG Shift (kg CO_2e/a)	SD	Building Energy (kg CO_2e/a)	SD	Land Use Shift (m^2/a)	SD	Runoff Reduction(m^3/a) - high	SD	Runoff Reduction (m^3/a) - low	SD	Waste Uptake (kg/a)	SD	Greens Produced (cup eq./a)	SD	Red and Orange Produced (cup eq./a)	SD	Other Produced (cup eq./a)	SD	Planted Area (m^2/a)	SD	Roof Area (m^2)	SD	Revenue (USD/a)	SD	Export (USD/a)	SD
1900	-3.93E+07	4.99E+04	1.43E+07	7.41E+04	-8.21E+05	1.63E+04	-5.55E+05	1.10E+04	5.68E+07	2.13E+03	1.83E+08	2.87E+03	1.75E+08	1.39E+03	2.14E+07	2.85E+04	4.60E+07	1.89E+05	1.33E+07	7.73E+04	1.85E+06	4.81E+04	1.00E+06	1.99E+04	-3.93E+07	4.99E+04
1910	-3.94E+07	5.29E+04	1.48E+07	7.85E+04	-4.46E+05	1.73E+04	-3.02E+05	1.17E+04	5.68E+07	1.14E+03	1.83E+08	4.19E+03	1.75E+08	7.36E+03	2.13E+07	2.44E+04	4.81E+07	1.65E+05	1.16E+07	8.12E+04	1.07E+06	5.04E+04	5.45E+05	2.11E+04	-3.94E+07	5.29E+04
1920	-3.93E+07	5.33E+04	1.50E+07	8.39E+04	-3.07E+05	1.44E+04	-2.08E+05	9.75E+03	5.68E+07	1.03E+03	1.83E+08	1.87E+03	1.75E+08	2.15E+03	2.13E+07	2.81E+04	4.88E+07	1.73E+05	1.09E+07	6.64E+04	7.50E+05	4.04E+04	3.75E+05	1.76E+04	-3.93E+07	5.33E+04
1930	-3.93E+07	5.28E+04	1.51E+07	7.61E+04	-2.32E+05	1.52E+04	-1.57E+05	1.03E+04	5.68E+07	1.06E+03	1.83E+08	4.97E+02	1.75E+08	1.25E+03	2.12E+07	2.64E+04	4.92E+07	1.49E+05	1.06E+07	7.03E+04	5.71E+05	4.34E+04	2.83E+05	1.86E+04	-3.93E+07	5.28E+04
1940	-3.93E+07	4.80E+04	1.52E+07	8.34E+04	-1.99E+05	1.47E+04	-1.35E+05	9.91E+03	5.68E+07	1.12E+03	1.83E+08	6.23E+02	1.75E+08	1.35E+03	2.12E+07	2.64E+04	4.93E+07	1.26E+05	1.04E+07	6.71E+04	4.94E+05	4.11E+04	2.43E+05	1.79E+04	-3.93E+07	4.80E+04
1950	-3.93E+07	4.78E+04	1.52E+07	7.35E+04	-1.81E+05	1.60E+04	-1.22E+05	1.08E+04	5.68E+07	1.10E+03	1.83E+08	4.92E+02	1.75E+08	1.10E+03	2.12E+07	2.47E+04	4.94E+07	1.74E+05	1.03E+07	7.18E+04	4.46E+05	4.91E+04	2.21E+05	1.95E+04	-3.93E+07	4.78E+04
1960	-3.93E+07	4.78E+04	1.53E+07	8.32E+04	-1.52E+05	1.33E+04	-1.02E+05	8.98E+03	5.68E+07	1.14E+03	1.83E+08	5.13E+02	1.75E+08	1.14E+03	2.12E+07	2.57E+04	4.95E+07	1.25E+05	1.02E+07	6.13E+04	3.68E+05	3.89E+04	1.85E+05	1.62E+04	-3.93E+07	4.78E+04
1970	-3.93E+07	4.68E+04	1.53E+07	8.09E+04	-1.19E+05	1.18E+04	-8.02E+04	7.98E+03	5.68E+07	1.12E+03	1.83E+08	5.20E+02	1.75E+08	1.41E+03	2.12E+07	2.50E+04	4.97E+07	1.57E+05	1.01E+07	5.44E+04	2.85E+05	3.49E+04	1.45E+05	1.44E+04	-3.93E+07	4.68E+04
1980	-3.93E+07	4.87E+04	1.53E+07	8.43E+04	-1.03E+05	8.77E+03	-6.97E+04	5.93E+03	5.68E+07	1.04E+03	1.83E+08	5.14E+02	1.75E+08	1.36E+03	2.12E+07	2.59E+04	4.97E+07	1.31E+05	9.98E+06	4.04E+04	2.46E+05	2.50E+04	1.26E+05	1.07E+04	-3.93E+07	4.87E+04
1990	-3.93E+07	5.19E+04	1.54E+07	6.96E+04	-7.66E+04	8.50E+03	-5.18E+04	5.74E+03	5.68E+07	1.09E+03	1.83E+08	5.21E+02	1.75E+08	1.21E+03	2.12E+07	2.06E+04	4.98E+07	1.33E+05	9.86E+06	3.77E+04	1.78E+05	2.46E+04	9.35E+04	1.04E+04	-3.93E+07	5.19E+04
2000	-3.93E+07	4.08E+04	1.54E+07	7.82E+04	-5.35E+04	7.96E+03	-3.62E+04	5.38E+03	5.68E+07	1.09E+03	1.83E+08	4.80E+02	1.75E+08	1.42E+03	2.12E+07	2.04E+04	5.00E+07	1.14E+05	9.76E+06	3.69E+04	1.26E+05	2.32E+04	6.53E+04	9.72E+03	-3.93E+07	4.08E+04

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